Runoff Generation during Heavy Rainfall Events: Integrating Expert Knowledge about Dominant Runoff Processes in Conceptual Hydrological Models

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Dissertation

zur

Erlangung der naturwissenschaftlichen Doktorwürde

(Dr. sc. nat.)

vorgelegt der

Mathematisch-naturwissenschaftlichen Fakultät

der Universität Zürich

von

Manuel Antonetti

aus

Italien

Promotionskommission

Prof. Dr. Jan Seibert (Vorsitz)

Prof. Dr. Ross Purves

Dr. Katharina Liechti

Dr. Massimiliano Zappa (Leiter)

Zürich, 2017

a Gabriel

Summary

Conceptual rainfall-runoff models perform well on gauged basins but show their limitations in reproducing the hydrological behaviour of ungauged catchments. This is due to the fact that catchment reaction to heavy precipitation depends on both catchment and rainfall characteristics. Understanding and modelling the dominant runoff processes (DRPs) involved in runoff generation is therefore a key objective of both "wet" (experimentalists) and "dry" (modellers) hydrologists. Both experimentalists and modellers agree that using expert knowledge can help to address this challenge. However, their use of expert knowledge differs for each step of the modelling procedure, which involves (1) hydrologically mapping the DRPs occurring on a given catchment, (2) parameterising these processes within a model, and (3) allocating its parameters. Modellers generally use very simplified, GIS-based, top-down mapping approaches, applying their knowledge in constraining the model by defining parameter and process relational rules. In contrast, experimentalists usually prefer to invest all their detailed qualitative knowledge about processes in mapping the spatial distribution of DRPs as realistic as possible, and in defining a priori narrow value ranges for each model parameter.

In the first study of this thesis, the extent to which the assumptions involved in simplified mapping approaches are applicable in other catchments was investigated. Three automatic approaches were therefore used to map two catchments on the Swiss Plateau. The resulting maps were compared to reference maps obtained with manual mapping. Measures of agreement and association, a class comparison, and a deviation map were computed. The automatically derived DRP maps were used in synthetic runoff simulations with an adapted version of the PREVAH hydrological model, and simulation results were compared with those from simulations using the reference maps. DRP maps derived with the most complex and data-intensive automatic approach were found to be the most similar to the reference maps, while those derived with simplified approaches without original soil information differed significantly in terms of both extent and distribution of the DRPs. The runoff simulations derived from the simpler DRP maps were more uncertain due to inaccuracies in the input data and their coarse resolution, but problems were also linked to the use of topography as a proxy for the storage capacity of soils.

In a second study, a bottom-up approach for simulations in ungauged basins was introduced. The approach relies on a process-based runoff generation module (RGM-PRO) able to exploit information from DRP maps. RGM-PRO is grid-based and, within each grid cell, the process heterogeneity is considered. This limits the computational costs and avoids information loss due to the grid resolution. The module is event-based, and initial conditions are assimilated and downscaled from continuous simulations of PREVAH, which are also available for real-time applications. A parameter allocation strategy was developed based on the results of sprinkling experiments, and was tested on several catchments on the Swiss Plateau and Pre-Alps. RGM-PRO simulated heavy rainfall events in a more realistic way than the non-calibrated traditional runoff generation module of PREVAH, and, in some instances, it even exceeded the performance of the calibrated traditional one. The use of information on the spatial distribution of DRPs additionally proved to be also valuable as a regionalisation technique, and showed ad-

vantages in terms of robustness and transferability over other regionalisation approaches, including a version of PREVAH that avoids calibration, one that transfers calibrated parameters, and one that uses regionalised parameter values.

As runoff simulations are affected by equifinality and numerous other uncertainty sources, the assumption that the more expert knowledge is used, the better the results will be was challenged in the third study of this dissertation. A total of 60 modelling chain combinations forced by five rainfall datasets of increasing accuracy was applied to four nested catchments in the Swiss Pre-Alps. These datasets include hourly precipitation data from automatic stations interpolated with Thiessen polygons and with the Inverse Distance Weighting method, as well as different spatial aggregations of Combiprecip, a combination between ground measurements and radar quantitative estimations of precipitation. To map the spatial distribution of the DRPs, three mapping approaches with different levels of involvement of expert knowledge were used. Furthermore, a typical modellers' top-down setup relying on parameter and process constraints was compared with the experimentalists' setup developed for the second study of this dissertation. The simulation results showed that the modelling chains based on the most complex DRP maps performed slightly better than those based on less expert knowledge. This is very likely due to compensation effects within the model. The bottom-up setup performed better than the top-down one when simulating short-duration events, but similarly to the top-down setup when simulating long-duration events. Finally, the analysis of variance performed to quantify the uncertainty sources highlighted the importance of a realistic representation of the spatial distribution of processes, as the uncertainty linked with the DRP maps increased with decreasing size of the catchments.

The first results from a pseudo-operation application of RGM-PRO are encouraging, as the model performed similarly or even better than the traditional calibrated conceptual module of PREVAH in the Emme catchment (Swiss Pre-Alps). In the Verzasca catchment (Swiss Alps), RGM-PRO outperformed the traditional forecasting chain in terms of mean absolute error, independently from the lead time and threshold quantile.

The findings of this thesis are expected to be (i) corroborated on catchments with contrasting hydrological behaviour and very accurate precipitation and runoff data; (ii) extended to address further hydrological issue beyond flood on, e.g., droughts or rain on snow processes; (iii) used as input for other investigations, as the more realistic spatial representation of DRPs within a given catchment entails the potential for improving studies on e.g. landslides, debris flows, large wood in torrents and rivers.

Zusammenfassung

Konzeptionelle hydrologische Modelle simulieren den Abfluss mit zufriedenstellender Genauigkeit in Einzugsgebieten, in denen Abflussmessungen vorhanden sind, zeigen aber ihre Grenzen in der Nachbildung des hydrologischen Verhaltens ungemessener Einzugsgebiete. Grund dafür ist die Tatsache, dass Einzugsgebiete, abhängig von den Gebiets- und Niederschlagsereigniseigenschaften, sehr unterschiedlich auf Starkniederschlag reagieren können,. Das Verständnis und die Modellierung der während der Abflussbildung beteiligten, dominanten Abflussbildungsprozesse (DRPs vom Englischen *Dominant Runoff Processes*) ist deswegen das Leitziel beider, „nasser" (Experimentalisten) und „trockener" (Modellierer) Hydrologen. Experimentalisten und Modellierer sind sich einig, dass dieser Herausforderung durch die Nutzung vom Expertenwissen über die DRPs begegnet werden kann. Deren Strategien zur Implementierung dieses Wissens weichen allerdings in jeder Phase des hydrologischen Modellierungsvorgehens ab. Dies besteht aus: (1) Der hydrologischen Kartierung der vorkommenden DRPs in einem vorgegebenen Einzugsgebiet; (2) Der Parametrisierung dieser DRPs im Rahmen eines hydrologischen Modells; (3) Der Allokation der Modellparameter. Modellierer verwenden meistens stark vereinfachte, GIS-basierte, *top-down* Kartierungsansätze, und wenden ihr Expertenwissen während der Modelleinschränkung (*model constraining*) an, durch die Festlegung von Bedingungen, die sowohl die Modellparameter als auch die simulierten Flüsse einhalten müssen. Im Gegensatz dazu bevorzugen Experimentalisten ihr detailliertes, qualitatives Prozessverständnis einzusetzen für eine möglichst realistische Bestimmung der räumlichen Verteilung der Abflussbildungsprozesse und für die a priori Festlegung von möglichst kleinen Anfangsbereichen für jeden Modellparameter.

In der ersten Studie dieser Doktorarbeit wurde die Übertragbarkeit der den stark vereinfachten Kartierungsansätzen zugrundeliegenden Hypothesen untersucht. Drei automatisierte Ansätze wurden für die Kartierung von zwei Einzugsgebieten im Schweizer Mittelland angewendet. Die resultierenden Prozesskarten wurden mit einer von Hand erstellten Prozesskarte (Referenzkarte) verglichen. In diesen Rahmen wurden Übereinstimmungs- und Zusammenhangsmasse berechnet, ein Klassenvergleich durchgeführt, und eine Abweichungskarte hergeleitet. Zudem wurden die automatisch hergeleiteten Prozesskarten für synthetische hydrologische Simulationen mit einer angepassten Version des hydrologischen Modells PREVAH verwendet. Die resultierenden simulierten Ganglinien wurden mit denjenigen verglichen, die aus Simulationen mit den Referenzkarten herstammten. Die mit dem grössten Datenbedarf und mit dem komplexesten Kartierungsansatz hergeleiteten Prozesskarten zeigten die grössten Übereinstimmungen mit den Referenzkarten. Die Prozesskarten, welche mit den stark vereinfachten Ansätzen hergeleitet wurden, zeigten hingegen die grössten Unterschiede in der Ausdehnung und Verteilung der DRPs. Die mit den vereinfachten Prozesskarten betriebenen Abflusssimulationen wiesen zudem die grössten Unsicherheiten auf. Dies ist den Ungenauigkeiten und der groben Auflösung der für die Herleitung der Prozesskarten verwendeten Input-daten zuzuschreiben. Probleme wurden aber auch mit der Verwendung topographischer Grössen als Indikator für die Speicherkapazität der Böden festgestellt.

In der zweiten Studie wurde ein *bottom-up* Ansatz für Simulationen ungemessener Eizugsgebiete vorgestellt. Der Ansatz beruht auf dem prozess-basierten Abflussbildungs-

modul RGM-PRO, das in der Lage ist, Informationen aus den Prozesskarten zu verwenden. RGM-PRO verfügt über eine gegitterte Diskretisierung. Für jede Gitterzelle wird die Heterogenität der Prozesse berücksichtigt, um einen vernünftigen Rechenaufwand zu ermöglichen und gleichzeitig Informationsverluste durch die Gitterauflösung zu vermeiden. Das Modul ist ereignisbasiert, und die Anfangsbedingungen bezüglich Bodenfeuchtezustand werden aus kontinuierlichen, für Echtzeitanwendungen verfügbaren Simulationen von PREVAH assimiliert. Eine Strategie zur a priori Feststellung der Anfangsbereiche der Modellparameter wurde anhand der Nachrechnung von Beregnungsversuchen entwickelt, und für verschiedene Einzugsgebiete des Schweizer Mittellands und der Voralpen getestet. RGM-PRO simulierte Starkniederschlagsereignisse realistischer als eine nicht kalibrierte Version des traditionellen Abflussbildungsmoduls von PREVAH. In einigen Fällen, konnte das neue Modell sogar bessere Leistungen als das traditionelle, kalibrierte Modul von PREVAH erreichen. Die Nutzung von Informationen bezüglich der räumlichen Verteilung der DRP hat sich zudem als wertvolles Regionalisierungsverfahren erwiesen, und zeigte Vorteile hinsichtlich der Zuverlässigkeit und Übertragbarkeit des prozess-basierten Verfahrens im Vergleich mit anderen auf PREVAH basierten Regionalisierungsansätzen, wie z.B. eine nicht kalibrierte Version, eine Version wo kalibrierte Parameterwerte zeitlich und räumlich übertragt werden, und eine Version, die auf regionalisierte Parameterwerte zurückgreift.

Da Abflusssimulationen von Äquifinalität sowie anderen Unsicherheitsquellen betroffen sind, wurde die Annahme, dass umso bessere Resultate erreicht werden können, je mehr Expertenwissen verwendet wird, im Rahmen der dritten Studie dieser Dissertation geprüft. Insgesamt 60 verschiedene Kombinationen von Modellierungsketten wurden mit fünf Niederschlagsdatensätzen aufsteigender Genauigkeit auf vier verschachtelte Einzugsgebiete in den Schweizer Voralpen angewendet. Die Niederschlagsdatensätze bestehen aus stündlichen Daten automatischer Niederschlagsstationen, die mit zwei verschiedenen Methoden (Thiessen Polygone und inverse Distanzgewichtung) interpoliert wurden, sowie aus drei verschiedenen räumlichen Aggregationen des Combiprecip-Produkts, das eine Kombination zwischen an Niederschlagsstationen gemessenen Daten und aus Radarbildern hergeleiteten, quantitativen Niederschlagsabschätzungen besteht. Um die räumliche Verteilung der DRP zu kartieren wurden drei Kartierungsansätze mit unterschiedlicher Beteiligung von Prozesswissen verwendet. Zudem wurde eine den Modellierern nahestehende *top-down* Modellkonfiguration, bei der Bedingungen zur Parameter- und Flüsseeinschränkung eingehalten werden müssen, mit der in der zweiten Studie vorgestellten, *bottom-up* Modellkonfiguration verglichen. Simulationsergebnisse zeigten, dass die auf den komplexesten Prozesskarten basierenden Modellierungsketten nur leicht bessere Resultate erzielt haben als diejenigen Modellierungsketten, welche auf vereinfachten Prozesskarten basierten. Grund dafür sind Kompensierungseffekte innerhalb des Modells. Die *bottom-up* Modellkonfiguration simulierte kurze Niederschlagsereignisse besser als die top-down Modellkonfiguration. Langandauernde Niederschlagsereignisse konnten hingegen mit vergleichbarer Güte simuliert werden. Die zur Quantifizierung der verschiedenen Unsicherheitsquellen durchgeführte Varianzanalyse (ANOVA) hob die grosse Bedeutung einer realistischen Darstellung der räumlichen Verteilung der DRP hervor und zeigte, wie die mit den Prozesskarten verbundene Unsicherheit mit der Verringerung der Einzugsgebietsgrösse zunahm.

Die allerersten Resultate aus einer pseudo-operationellen Anwendung von RGM-PRO sind vielversprechend. Das neue Modul konnte in allen untersuchten Teileinzugsgebieten der Emme (Schweizer Voralpen) ähnliche und teilweise bessere Resultate als das traditionelle Abflussbildungsmodul von PREVAH erzielen. Im Einzugsgebiet der Verzasca (Schweizer Alpen), übertraf RGM-PRO, unabhängig vom Vorhersagehorizont und vom Abflussschwellenwert, die Leistung der traditionellen Vorhersagekette hinsichtlich des mittleren absoluten Fehlers.

Die Forschungsergebnisse aus dieser Doktorarbeit könnten (i) auf Einzugsgebiete mit stark unterschiedlichen Abflussreaktion auf Starkniederschlag und mit zuverlässigen verfügbaren Niederschlags- und Abflussdaten konsolidiert werden; (ii) erweitern werden, indem weitere hydrologische Fragestellungen wie z. B. Trockenheit oder Regen-auf-Schnee-Prozesse mit dem DRP-Ansatz in Angriff genommen werden; (iii) als Ausgangslage für weitere Untersuchungen dienen, da eine realistischere Darstellung der räumlichen Verteilung der Abflussbildungsprozesse innerhalb eines Einzugsgebietes Studien bspw. über Hangrutschungen, Murgänge oder Schwemmholz in Gewässern, potentiell verbessern kann.

Sommario

I modelli idrologici concettuali sono generalmente performanti su bacini idrografici strumentati mentre mostrano le proprie limitazioni qualora applicati su bacini privi di misurazioni di portata. Questo accade perché la reazione di un bacino alle precipitazioni è condizionata sia dalle caratteristiche del bacino stesso sia da quelle dell'evento considerato. La comprensione e la modellazione dei processi che dominano la formazione del deflusso (cosiddetti DRP dall'inglese "*Dominant Runoff Process*") è perciò uno degli obiettivi chiave sia degli idrologi sperimentalisti (*experimentalists)* che degli idrologi modellisti (*modellers).* Entrambe le categorie concordano sull'utilizzo di conoscenza specialistica (*expert knowledge*) per affrontare la questione; tuttavia, esse discordano sul metodo di implementazione della suddetta conoscenza in ciascuna delle fasi di modellazione, che consiste: (1) nella mappatura dei DRP di un determinato bacino; (2) nella parametrizzazione di ciascun processo all'interno di un modello; e (3) nella allocazione dei parametri del modello stesso. I modellisti adottano, generalmente, delle tecniche di mappatura piuttosto semplificate, preferendo utilizzare la propria conoscenza specialistica per stabilire regole relazionali sia tra i parametri del modello che tra i flussi modellati. Al contrario, gli sperimentalisti tendono ad investire la loro dettagliata e qualitativa conoscenza sui processi al fine di ottenere distribuzioni spaziali dei DRP il più realistiche possibile, nonché definendo a priori stretti *range* iniziali per ogni parametro del modello.

Nel primo studio di questa tesi, la trasferibilità delle ipotesi alla base di alcune tecniche semplificate di mappatura dei DRP è stata messa alla prova. Tre algoritmi automatici di mappatura sono stati utilizzati per mappare i DRP in due bacini sull'Altipiano svizzero. Le mappe risultanti sono state confrontate con una mappa di riferimento tracciata manualmente. Per il raffronto, sono stati calcolati il grado di concordanza e di associazione, sono state stilate delle mappe di deviazione ed è stato condotto un confronto tra classi. Inoltre, le mappe automatiche dei DRP sono state usate per simulazioni di portata sintetiche con una versione adattata del modello idrologico PREVAH, e i risultati sono stati confrontati con simulazioni sintetiche effettuate con la mappa di riferimento. Le mappe dei DRP ricavate con la tecnica di mappatura automatica più complessa e dispendiosa si sono rivelate essere le più simili alle mappe di riferimento, mentre le mappe ricavate con i metodi semplificati, che non usano informazioni sul suolo, si discostano dalle mappe di riferimento in termini sia di estensione che di localizzazione dei DRP. Le simulazioni di portata condotte con le mappe semplificate sono risultate essere affette da maggiore incertezza, dovuta principalmente alla presenza di imprecisioni e alla scarsa risoluzione delle mappe in input. Infine, sono stati riscontrati problemi legati all'uso di grandezze topografiche come indicatori della capacità di immagazzinamento dell'acqua nel suolo.

Lo studio successivo presenta un approccio bottom-up per simulazioni di portata in bacini privi di misurazioni. L'approccio si basa su un modulo di generazione del deflusso (RGM-PRO) in grado di sfruttare le informazioni presenti nelle mappe dei DRP. RGM-PRO è un modello su griglia e, all'interno di ogni cella, l'eterogeneità dei processi è considerata in modo tale da velocizzare le simulazioni evitando al tempo stesso la perdita di informazioni a causa della risoluzione spaziale della griglia stessa. RGM-PRO è inoltre un modulo ad evento, le cui condizioni iniziali vengono assimilate da simulazioni continue di PREVAH, disponibili per applicazioni in tempo reale. Una strategia per

l'allocazione dei parametri di RGM-PRO, sviluppata sulla base di esperimenti a pioggia controllata, è stata applicata con successo in diversi bacini sull'Altipiano e sulle Prealpi svizzere. RGM-PRO è stato in grado di simulare eventi di precipitazione estrema in maniera più realistica rispetto al tradizionale modulo di generazione del deflusso di PREVAH non calibrato. In alcuni casi, RGM-PRO è stato in grado di fornire prestazioni migliori rispetto alla sua controparte tradizionale e calibrata. L'uso di informazioni relative alla distribuzione spaziale dei DRP si è rivelato essere valido anche come tecnica di regionalizzazione, mostrando vantaggi in termini di robustezza e trasferibilità rispetto ad altri metodi, tra cui una versione di PREVAH priva di calibrazione, una in cui i parametri calibrati su un bacino ed un evento vengono trasferiti in spazio e tempo, e una in cui i parametri stessi vengono regionalizzati.

Data la presenza di equifinalità, oltre a numerose altre fonti di incertezza, nelle simulazioni di portata, l'ipotesi che un maggior uso delle conoscenze specialistiche implichi un miglioramento dei risultati delle simulazioni è stata discussa nel terzo studio di questa tesi. Un totale di 60 diverse combinazioni di modello, forzate con cinque set di dati di precipitazione con crescente grado di accuratezza, è stato applicato a quattro bacini sulle Prealpi svizzere. I dati di precipitazione includono dati di pioggia oraria da stazioni meteorologiche automatiche, interpolati con due diversi metodi (poligoni di Thiessen e *Inverse Distance Weighting*), nonché tre diverse aggregazioni spaziali di Combiprecip, una combinazione tra misurazioni a terra e stime quantitative di precipitazione da immagini radar. Per mappare la distribuzione spaziale dei DRP sono invece state utilizzate tre tecniche di mappatura con un crescente coinvolgimento di conoscenza specialistica. In aggiunta, una configurazione tipica dei modellisti (*top-down*), basata su regole relazionali valide su parametri e flussi, è stata confrontata con la configurazione tipica degli sperimentalisti (*bottom-up*) sviluppata nel corso del secondo studio. I risultati delle simulazioni lasciano dedurre che le combinazioni di modello basate sulle mappe dei DRP ottenute col metodo più complesso sono solo marginalmente superiori rispetto alle combinazioni basate su tecniche di mappatura semplificate. Questo è da attribuire alla presenza di effetti di compensazione tra classi all'interno del modello. La configurazione bottom-up ha raggiunto risultati migliori di quella top-down per quanto riguarda la simulazione di eventi di breve durata, mentre entrambe le configurazioni hanno raggiunto risultati comparabili nella simulazione di eventi di lunga durata. Infine, l'analisi delle varianza (*ANOVA*), effettuata per quantificare le diverse fonti di incertezza, ha sottolineato l'importanza di una rappresentazione realistica della distribuzione spaziale dei DRP, dato l'aumentare dell'incertezza dovuta alle mappe dei DRP al diminuire della dimensione del bacino.

I primi risultati di una applicazione pseudo-operazionale di RGM-PRO sono incoraggianti, dato che il modello ha fornito risultati simili o addirittura migliori rispetto a quelli forniti dal modulo tradizionale di generazione del deflusso di PREVAH per il bacino della Emme (Prealpi svizzere). Quanto al bacino della Verzasca (Alpi svizzere), RGM-PRO ha superato la catena tradizionale di previsione idrologica in termini di errore medio assoluto, indipendentemente dal *lead time* e dal quantile in considerazione.

Si suppone che i risultati di questa tesi possano venire (i) corroborati su bacini con comportamento idrologico contrastante e sui quali siano disponibili cui dati accurati di precipitazione e portata; (ii) estesi ad altre tematiche idrologiche oltre alle piene, ad esempio processi di siccità o pioggia su neve; (iii) usati come input per ricerche future, dato che una rappresentazione spaziale più realistica dei DRP all'interno di un determinato bacino rappresenta un potenziale di miglioramento, ad esempio, negli studi sui processi di frane e smottamenti, colate detritiche, e trasporto solido per flottazione.

List of papers and authors' contribution

The present dissertation entitled "Runoff Generation during Flash Floods: Integrating Expert Knowledge about Dominant Runoff Processes in Conceptual Hydrological Models" consists of three papers and an introductory part that furnishes a background, a summary and an outlook of the work done. In addition, two further studies conducted during the PhD project are included as appendix.

Following papers are object of this dissertation:

I. Antonetti, M., Buss, R., Scherrer, S., Margreth, M., and Zappa, M.. 2016. Mapping dominant runoff processes: an evaluation of different approaches using similarity measures and synthetic runoff simulations. *Hydrology and Earth System Sciences* 20 (7): 2929–2945 DOI: 10.5194/hess-20-2929-2016

II. Antonetti, M., Scherrer, S., Kienzler, P. M., Margreth, M. and Zappa, M.. 2017. Process-based hydrological modelling: the potential of a bottom-up approach for runoff predictions in ungauged catchments. *Accepted for publication in Hydrological Processes.* DOI: 10.1002/hyp.11232

III. Antonetti, M. and Zappa, M.. In review, 2017. How can expert knowledge increase the realism of conceptual hydrological models? A case study in the Swiss Pre-Alps. *Hydrol. Earth Syst. Sci. Discuss*. DOI: 10.5194/hess-2017-322

AI. Antonetti, M., Scherrer, S., Kienzler, P.M., Margreth, M., and Zappa, M. 2016. Überprüfung eines prozessnahen Abflussbildungsmoduls auf der Hangskale und in klein- und mesoskaligen Gebieten. In *Forum Für Hydrologie und Wasserbewirtschaftung* 36.16: 63–74.

AII. Horat, C., Antonetti, M., Wernli, H., and Zappa, M. (in preparation). Operational application of a process-based runoff generation module in the Swiss Alps and Pre-Alps. In preparation for *Natural Hazards and Earth System Sciences*.

Paper I is based on the outcomes of Rahel Buss's (IfU-ETHZ) master thesis. I was responsible for the design of the comparisons and simulations, whereas the student performed most of them. The co-authors produced the reference and the SF07 maps, the student and I derived the MU09 and GH11 maps. I finally prepared the manuscript with contributions from the co-authors. In papers II, III and AI, I was responsible for the model development, the execution of simulations, the analysis of simulation results and the main part of writing, whereas the co-authors produced the DRP maps. Finally, Paper AII is based on the outcomes of Christoph Horat's (IAC-ETHZ) master thesis. I was responsible for the design of the simulations, whereas the student performed most of them.

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List of abbreviations

Abbreviation	Long name/description
ANOVA	ANalysis Of VAriance
BETA	Non-linearity parameter for infiltration module
CG1H	Storage time for quick baseflow
CPC	Combiprecip
CPC.mean	Combiprecip averaged over the whole catchment
CPC.mean.subc	Combiprecip averaged over the whole corresponding sub-catchment
CPERC	Maximum percolation rate
DP	Deep Percolation
DRP	Dominant Runoff Process
GH11	Mapping approach after Gharari et al. (2011)
GS1H	Storage time for concentration of subsurface flow
GOF	Goodness Of Fit
HAND	Height Above the Nearest Drainage
HD	Hydrological Downscaling
HOF	Hortonian Overland Flow
IDW	Precipitation interpolated with the Inverse Distance Weighting method
K0H	Storage time for overland flow
K1H	Storage time for subsurface flow
K2H	Storage time for slow baseflow
KGE	Klingt-Gupta Efficiency
MC	MapCurves
MU09	Mapping approach after Müller et al. (2009)
NSE	Nash-Sutcliffe Efficiency
P	Precipitation
PREVAH	PREecipitation-Runoff-EVApotranspiration HRU Model
Q	Discharge
R	Routing
RC	Runoff Concentration
RG	Runoff Generation
RGM-PRO	PROcess-based Runoff Generation Module
RMSE	Root Mean Squared Error
RT	Runoff Type
SF07	Mapping approach after Margreth et al. (2010) and Schmocker-Fackel et al. (2007)
SGRLUZ	Thresold for overland flow
SLZ	Lower zone runoff storage
SLZ1MAX	Maximal content of the quick baseflow storage
SN03	Mapping approach after Scherrer AG (2006) and Scherrer and Naef (2003)
SOF	Saturation Overland Flow
SSF	SubSurface Flow
SSM	Soil moisture storage
SUZ	Upper zone runoff storage
THI	Precipitation interpolated with Thiessen polygons

1. Introduction

The aim of this introductory chapter is to give an overview of the research field, in which this dissertation is framed. The importance of the PhD project is claimed in §1.1, whereas the concept of Dominant Runoff Process (DRP), on which the dissertation is built on, is defined in §1.2. Section 1.3 contains the state of the art on the integration of process understanding in conceptual, spatially distributed hydrological models based on the DRP concept. Based on strengths and limitations of the applications reviewed in §1.3, research gaps and correspondent research questions are formulated in §1.4.

1.1 Motivation

The fifth assessment report of the Intergovernmental Panel on Climate Change confirms that warming of the climate system is unequivocal (IPCC, 2014). The most evident consequences concern the increase of global average air and ocean temperatures, and in turn the faster melting of snow and ice and the rising of the global average sea level. Recently, Fischer and Knutti (2016) confirmed that the frequency of heavy precipitation events has increased and will increase over most land regions With regard to Switzerland, both intensity and frequency of heavy precipitation increased in observations for the years 1901–2014 (Scherrer et al., 2016). This had clear implications for natural hazards triggered by heavy precipitation, floods being one of them, as changes in atmospheric circulations are responsible for flood frequency fluctuations (Schmocker-Fackel and Naef, 2010a). For instance, Schmocker-Fackel and Naef (2010b) analysed changes in flood frequency in Switzerland since 1850. Negative trends were found only in few stations, whereas flood frequency increased in most stations, especially with the inclusion of period between 2001 and 2007 in the analysis. A reason for that is represented by the flood which affected large parts of Northern Switzerland in August 2005, causing six casualties and nearly 3 billion Euro damages (Hegg et al., 2008). More generally, the total amount of financial damages due to floods, debris flows, landslides and rockfalls for the period 1972-2007 was estimated at nearly 8 billion Euro (Hilker et al., 2009).

One of the main tasks of hydrologists is therefore to help improving the management and reducing the risk of floods. This can be achieved on both long and short time horizons. Over the long-term, *prevention* measures like defence structures or restoration of rivers' natural flood zones can be undertaken. Over the short-term, the *prediction* of heavy precipitation events is crucial to gain precious time for emergency population warning or carrying out *mitigation* measures. Hydrological predictions are particularly challenging on ungauged (i.e. not measured) catchments, given that runoff data is only available for a small percentage of the catchments throughout the world (Hrachowitz et al., 2013).

The techniques developed for this purpose can be grouped into statistical and process-accounting methods (Blöschl et al., 2013). The statistical methods establish empirical relationships between catchment characteristics and runoff, based on either indices, regression models or geostatistics. However, these methods do not consider explicitly the processes involved in the runoff generation, and therefore strongly dependent on the amount and quality of the data used for deriving them (e.g. Klemeš, 2000). Conversely, process-accounting methods are based on the hydrologist's understanding of the catchment and rely on the assumption that, by simulating the runoff processes in a realistic manner, good extrapolation over space and time can be achieved. To address this challenge, therefore, two research directions have been established in the recent decades: the *modellers* and the *experimentalists* (Seibert and McDonnell, 2002). The modellers try to interpret and reproduce measured hydrographs using simplified models, but these need calibration and are therefore not directly applicable to ungauged catchments unless an approach for transferring the parameter values is available. The experimentalists try to understand the processes at the field scale and then upscale their knowledge to larger scales. However, such an approach may be too data demanding and not flexible enough to cope with emergent patterns at large scales (Beven, 2000).

The overall aim of this thesis is therefore to couple the two above-mentioned approaches or, in other words, to implement the process understanding in the modelling process, to reduce the predictive uncertainty of rainfall-runoff models and, therefore, to improve the quality of hydrological simulations. Among the different strategies for integrating expert knowledge on runoff processes available in literature (e.g. Clark et al., 2011, 2015a, 2015b; McMillan et al., 2011), the concept of *dominant runoff process* (DRP; Blöschl, 2001) was used for this thesis.

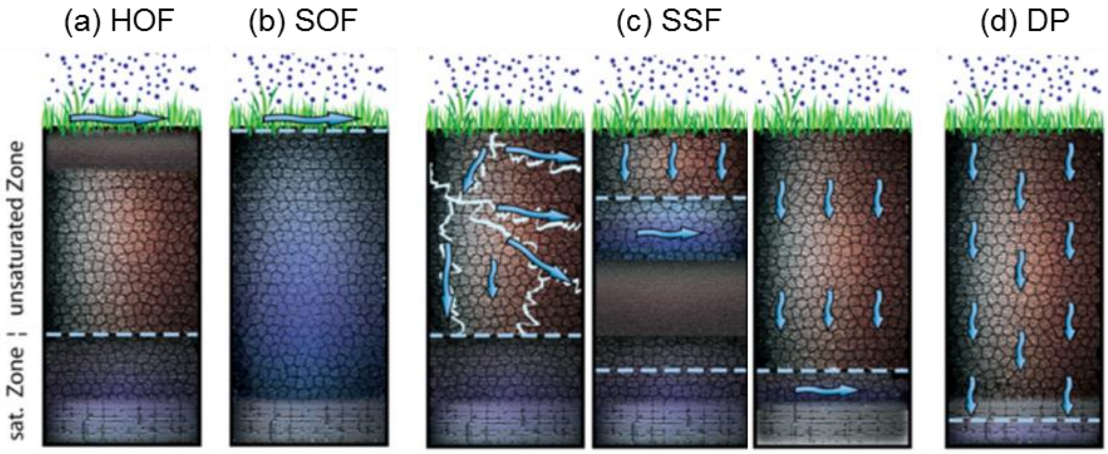


Figure 1.1 Different types of surface and subsurface runoff processes: (a) Hortonian overland flow (HOF), (b) Saturated overland flow (SOF), (c) Subsurface flow (SSF) due to the presence of macropores, an impermeable soil layer or an impermeable bedrock; (d) Deep percolation (DP). Adapted from Rinderer and Seibert (2012).

1.2 The concept of Dominant Runoff Process - DRP

In recent decades, several methods have been developed to include process understanding in conceptual hydrological models. For instance, the topographical wetness index (Beven and Kirkby, 1979) allows areas prone to HOF to be identified using only topographical information. A recent approach consists of the formulation of recommendations for representing processes in hydrological models based on the analysis of field data. For instance, McMillan et al. (2011) used precipitation, soil moisture and runoff data to derive the dominant hydrological mechanisms and suggest suitable mathematical representation by means of diagnostic tests. However, the recommendations proposed reflect the understanding of the possible processes involved at the lumped catchment scale only. Another methodology involves the explicit definition of hydrological response units (HRUs; Flügel, 1995; Ross et al., 1979), i.e. areas within a catchment characterized by similar hydrological behaviour. HRUs could be classified according to information on topography, geology, land use, and soil, and results can be usually visualised in form of maps. For example, Markart et al. (2004) developed a method for the assessment of surface runoff coefficients and surface roughness in case of extreme precipitation events by means of criteria based on characteristics of soil and vegetation. Although these methods represent an important basis for determining runoff peaks and return periods of flood events, they do not refer explicitly to the hydrological processes occurring on a site.

Different runoff generation mechanisms can occur on a given location, depending on its characteristics such as topography, land use, soil properties, and underlying geology, as well as the characteristics of the rainfall event, e.g. rainfall intensity and duration (Scherrer and Naef, 2003; Scherrer, 1997). For example, overland flow can occur if the infiltration capacity (Figure 1.1a) or storage capacity (Figure 1.1b) of soil is exceeded (Dunne and Black, 1970; Horton, 1933). Different mechanisms can lead to the formation of subsurface flow (Figure 1.1c): macropores generated e.g. by worms (Weiler and Naef, 2003), or the presence of a water-repellent soil layer, either within the soil profile or at

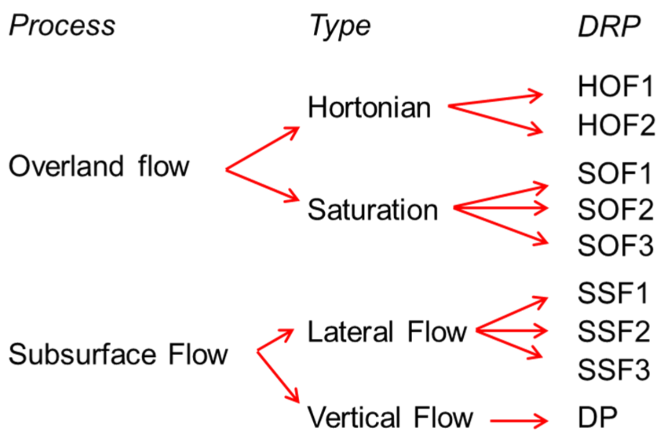


Figure 1.2 The different flow processes considered in the DRP classification proposed by Scherrer and Naef (2003). HOF = hortonian overland flow; SOF = saturation overland flow; SSF = subsurface flow; DP = deep percolation; D = tile drains. 1 represents an almost immediate reaction, 2 a slightly delayed one and 3 a strong delayed one.

the soil-bedrock interface (Rinderer and Seibert, 2012). Finally, if both soil and underlying bedrock are highly permeable, deep percolation occurs (Figure 1.1d). In this case, the infiltrating water drains to the groundwater store and does not significantly contribute to the storm flow, even during intense rainfall events (e.g. Onda et al., 2001).

The interplay between catchment and rainfall characteristics determines which runoff process contributes most to runoff, i.e. the *dominant runoff process* (DRP; Blöschl, 2001). Based on the results from sprinkling experiments performed on several grassland sites in Switzerland (Faeh et al., 1997a; Scherrer, 1997), Scherrer and Naef (2003) developed both a DRP classification with nine classes (Figure 1.2) and a decision scheme to indicate the likely DRP on temperate grassland hillslopes. Based on these schemes, the spatial distribution of DRPs within a catchment can be visualised in a so called “DRP map” or “process map”. Such maps contain, therefore, valuable information that can be used to either inform or build a hydrological model. Also, hydrological classifications based on landscapes with similar hydrological behaviour can be useful tools for predictions in ungauged basins, as once a model structure and its parameters have been identified for each landscape in a gauged catchment, they can be transferred to an ungauged catchment where the landscapes have similar hydrological behaviour (e.g. Beran, 1990; Mosley, 1981; Viviroli et al., 2009b).

1.3 Modelling strategies based on the DRP concept

1.3.1 DRP mapping approaches

Rule-based approaches for the mapping of dominant runoff processes (DRPs) aim at meaningfully classifying a catchment and reducing the parameters of spatially distributed conceptual models (Ley et al., 2011). It is possible to distinguish between two mapping strategies (Schmocker-Fackel et al., 2007). In a *top-down* classification, homogeneous units are defined with the help of a geographical information system (GIS) assuming

Table 1.1 DRP mapping approaches. HOF = hortonian overland flow; SOF = saturation overland flow; SSF = subsurface flow; DP = deep percolation; D = tile drains. 1 represents an almost immediate reaction, 2 a slightly delayed one and 3 a strong delayed one.

Author(s)	Approach	Input Data	Classes
Boorman et al. (1995)	TD	Soil map	29
Tilch et al. (2002, 2006)	TD	DTM, topographical and geological map	6 (HOF, SOF, SSF1-3, DP)
Gharari et al. (2011); Nobre et al. (2011) Rennó et al. (2008)	TD	DTM	Wetland (SOF), Hillslope (SSF), Plateau (DP), Bare soil/rock (HOF+DP)
Peschke et al. (1999)	BU	Soil map, geological map, DTM, land use map.	7 (HOF, SOF, Interflow1-2, Storage1-2, DP)
Waldenmeier (2003)	BU	Forestry site map (1:10’000), and DTM	7 (HOF, SOF+DP, SOF1-2, SSF1-2, DP)
Tetzlaff et al. (2007)	BU	DTM (10x10 m^2), geological map, soil map, land use map, aerial photographs, and field investigations.	5 (HOF, SOF, SSF1-2, DP)
Scherrer and Naef (2003); Scherrer AG (2006)	BU	16 datasets, and 15 soil profile properties (for a complete list see Scherrer and Naef, 2003)	9 (HOF1-2, SOF1-3, SSF1-3, DP)
Schmocker-Fackel et al. (2007) Margreth et al. (2010) Smoorenburg (2015)	BU	DTM (25x25 m^2), soil map (1:5’000), forest vegetation map (1:5’000), geological map (1:50’000), drainage map (1:25’000), landscape model (1:25’000).	12 (HOF1-2, SOF1-3, SSF1-3, D1-3, DP)
Müller et al. (2009); Hümann and Müller (2013)	BU	DTM (20x20 m^2), geological map (1:25’000), land use map.	9 (HOF1-2, SOF1-3, SSF1-3, DP)

that their hydrological response will also be homogeneous. Conversely, in a *bottom-up* classification, units with the same DRP are identified by means of extensive field investigations. Then, GIS-based methods are used to spatially extrapolate the results of the field investigations to larger areas. Table 1.1 shows a list of different mapping approaches based on DRPs. They differ from each other in terms of input data requirements, classification criteria, and hydrological output classes.

Top-down mapping approaches

Boorman et al. (1995) developed the HOST (Hydrology Of Soil Types) classification of Great Britain using soil information. They identified 29 classes with different expected hydrological behaviour based on conceptual models of the processes that occur in the soil. However, the relatively small scale of the published map (1:250’000) limits its suitability for runoff investigations in small catchments. Tilch et al. (2002) developed a classification approach based on the genesis of the hillslope and its covering material. A DEM, as well as topographical and geological maps, were firstly combined to define quaternary drift covers. Therefore, HRUs were determined discerning between surface (HOF; SOF),

Table 1.2 Classification criterion and classes of different topography-based mapping approaches.

Authors	Study area	Classification criterion	Landscapes classes and correspondent DRP
Rennò et al. (2008); Nobre et al. (2011)	Amazonia	HAND, slope	Waterlogged, Ecotone, Slope, Plateau
Savenije (2010); Gharari et al. (2011); Gharari et al. (2014)	Europe	HAND, slope	Wetland (SOF), Hillslope (SSF), Plateau (DP)
Gao et al. (2014)	China	HAND, elevation, slope, aspect	Wetland/Terrace (SOF), Grass Hillslope (SSF), Forest Hillslope (SSF), Bare soil/rock (HOF+DP)

interflow (SSF1-3) and base flow generating processes (DP). The method showed to be suitable for both periglacial zone and mesoscale mountain basins (Tilch et al., 2006). However, it is only applicable to areas with similar hillslope genesis (Tilch et al., 2006). In addition, the HRUs derived are time invariant, meaning that precipitation characteristics are not taken into account. In another study, Rennó et al. (2008) introduced a metric for hydrological classification based exclusively on topographical information, that is the Height Above the Nearest Drainage (HAND). The HAND metric normalises topography according to the local relative heights found along the drainage network. Normalised draining potentials can then be classified according to the relative vertical flow path-distances to the nearest drainages (Nobre et al., 2011). Rule-based approaches for the mapping of dominant runoff processes (DRPs) aim at meaningfully classifying a catchment and reducing the parameters of spatially distributed conceptual models (Ley et al., 2011). It is possible to distinguish between two mapping strategies (Schmocker-Fackel et al., 2007). In a top-down classification, homogeneous units are defined with the help of a geographical information system (GIS) assuming that their hydrological response will also be homogeneous. Conversely, in a bottom-up classification, units with the same DRP are identified by means of extensive field investigations. Then, GIS-based methods are used to spatially extrapolate the results of the field investigations to larger areas. Table 1.1 shows a list of different mapping approaches based on DRPs. They differ from each other in terms of input data requirements, classification criteria, and hydrological output classes. Table 1.2 reports different combinations of topographical controls for hydrological classifications, as available in literature. Classes and criteria were selected based on the location of each study area.

Bottom-up mapping approaches

The XPS-FLAB model (Peschke et al., 1999) represents one of the first bottom-up tools for the catchment discretisation based on DRP. The model requires both catchment and event related characteristics as input data. Information about the catchment is first overlaid and then classified using a set of rules based on experimental investigations and expert knowledge about the runoff generation physics. XPS-FLAB produces the spatial distribution of the different DRPs depending on the characteristics of the event, i.e. rainfall intensity and duration, as well as soil moisture. In a further approach, DRP classes are determined with a decision tree based on information from a forestry site map (Waldenmeyer, 2003). HOF is assigned to areas with very low hydraulic conductivity, whereas saturation overland flow is expected to occur on areas with high values of ecological wetness, as well as the presence of specific indicator plants. Areas characterised by subsurface flow and deep percolation are identified using soil layering information. Waldenmeyer's (2003) mapping approach is strongly linked to specific features (e.g. geology) of the catchment where it was developed, i.e. the Dürreych catchment (7 km^2) in the Northern Black Forest (Germany). Therefore, adjustments are needed for transferring the approach to another area.

Based on sprinkling experiments and soil investigations (Faeh et al., 1997b; Scherrer, 1997; Weiler and Naef, 2003), Scherrer and Naef (2003) developed decision schemes to determine the DRP at the plot scale. The structure of each scheme corresponds to that of a soil column, and consists of a sequence of vegetation cover, topsoil, subsoil, and bedrock. As one moves along the scheme network, decisions need to be made based on which criteria are fulfilled. At the end of each branch, a particular DRP can be defined. The event variability is taken into account distinguishing between long-duration events with medium intensities and short-duration events with high intensities. The input data required for the method of Scherrer AG (2006) comprise 16 datasets, whereas the field investigations require the measurement of 15 soil profile properties (see also Scherrer and Naef, 2003). This consistent data load limits the application of the schemes in mesoscale basins. To limit the data requirement for mapping, simplifications of the decision schemes have been proposed. For example, Schmocker-Fackel et al. (2007) developed a set of rules which allows the DRPs to be determined within a GIS environment. The approach relies on a soil map with high resolution (1:5000) of the Canton of Zurich. However, the soil map does not contain all the parameters required by the SN decision scheme (e.g. macroporosity, impermeable layers or lateral preferential pathways). Thus, the missing information was inferred from other maps, such as maps of forest vegetation, land use, geology, topography, as well as plans of artificially drained areas (Margreth et al., 2010). The simplified mapping approach was tested in two catchments on the Swiss Plateau and compared well with maps derived manually with the Scherrer and Naef's (2003) approach. Müller et al. (2009) suggested a further GIS-based approach that avoids the use of soil information. Their method identifies the same DRP classes as Scherrer and Naef (2003), but based exclusively on information about topography, land use, and geology. Hümann and Müller (2013) further developed the approach by considering both sealing effects on agricultural areas and the DRP dependency on rainfall type. Recently, Smoorenburg (2015) extended the mapping approach of Schmocker-Fackel et al. (2007) and Margreth et al. (2010) for alpine catchments, by further distinguishing between fast and slow deep percolation.

1.3.2 Integration of spatial distributed information on DRPs in conceptual hydrological models

DRP-based models differ from each other in terms of DRP mapping approach, flexibility of the model structure, temporal and spatial discretization used. With regard to the flexibility of the model structure, in a "one-size-fits-all" approach, the model structure is fixed and only the parameter sets change for each DRP. In contrast, within a flexible

Table 1.3 Overview of integration approaches of spatially distributed information on DRPs in conceptual hydrological models; TS = Temporal Scale; CO = Continuous; EB = Event-based; HRU = Hydro-logical Response Unit; RGM = Runoff generation module.

Model	Author(s)	DRP mapping approach	TS	Spatial discreti-sation	Model structure	Parameter allocation
LARSIM	Haag et al., (2016)	Scherrer and Naef (2003)	CO	Grid-based	One parameter set for each HRU	Calibration
LARSIM	Casper et al.(2015); Gronz (2013)	Steinrücken and Behrens (2010)	CO	HRU-based	One parameter set for each HRU	Calibration
QArea	VAW (1994); Horat (2000)	Scherrer and Naef (2003)	EB	HRU-based	One response curve for each HRU	A priori definition
QArea-pro	Schmocker-Fackel (2004)	Based on Scherrer and Naef (2003)	EB	HRU-based	One module for each HRU	A priori defini-tion
QArea^{+}	Smoorenburg (2015)	Based on Scherrer and Naef (2003)	EB	HRU-based	One model configu-ration for each HRU	A priori definition
KAMPUS (aka Flash Flood Model)	Reszler et al. (2006); Blöschl et al. (2008); Rogger et al. (2012)	Markart et al. (2004)	CO	Grid-based	One parameter set for each HRU	A priori def. (Reszler et al., 2006; Blöschl et al., 2008); manu-al calibr. Rogger et al. (2012)
ZEMOKOST	Kohl and Stepanek (2005)	Markart et al. (2004)	EB	HRU-based	One runoff coeffi-cient for each HRU, calculation of flow times	A priori definition
TACD	Uhlenbrook et al. (2004)	Tilch et al. (2002)	CO	Grid-based	Sequentially con-nected RGMs	Manual calibration
Runoff Coef-ficient Model	Carver et al. (2009)	Carver et al. (2009)	CO	Grid-based	One runoff coeff. for each HRU	A priori definition
Process Model	Rosin (2010)	Rosin (2010)	EB	Grid-based	One specific combi-nation of RGMs for each HRU	Calibration
RoGeR	Steinbrich et al. (2016)	Steinbrich et al. (2016)	EB	Grid-based	One parameter set for each DRP	A priori definition
DRP Model	Hellebrand et al. (2011)	Müller et al. (2009)	CO	HRU-based	One RGM for each HRU	Calibration
FLEX-topo	Fenicia et al. (2016); Gao et al. (2014); Gharari et al. (2014)	Gharari et al. (2011)	CO	HRU-based	One RGM for each HRU	Calibration

framework, both model structure and parameter set are developed specifically for each DRP. Depending on whether the evapotranspiration is directly simulated, it is also possible to discern between continuous and event-based models. The former are able to simulate the saturation conditions of a catchment before a precipitation event occurs, whereas the latter need assumptions on these. Finally, depending on their spatial discretization, DRP-based models can be either semi-distributed or grid-based. A brief description of conceptual hydrological models relying on the DRP concept is given (Table 1.3).

The Large Area Runoff Simulation Model (LARSIM) is a conceptual hydrological model used for simulations of flood protection planning, land use changes, and effects of climate change on water resources (Bremicker, 2000). Recently, Haag et al. (2016) integrated information on DRPs in an existing version of LARSIM for the Nahe catchment in Rhineland-Palatine, Germany. They modified the original model concept to adequately account for the effect of the different DRPs. The infiltration module was adapted to account for the different mechanisms that generate overland flow, i.e. Hortonian and saturation overland flow. Fast subsurface flow is generated based on a preferential flow function with the assumption that it becomes more likely with increasing saturation of the soil. Moreover, the preferential flow function allows deep percolation to occur. For each DRP, a parameter set is determined based on numerical experiments. The model was finally calibrated on two sub-basins of the Nahe catchment, and the relative differences among parameter values of different DRPs were kept constant. However, no significant improvement was detected with respect to simulations of high runoff peaks with the traditional LARSIM. Similarly, Casper et al. (2015) developed a parameterisation strategy for LARSIM based on previous investigations of the model parameter space of LARSIM. By doing so, it is ensured that the spatial process representation is maintained during the calibration of the model (Gronz, 2013).

QArea is an event-based rainfall-runoff model developed in Switzerland (VAW, 1994). It is based on response curves obtained from idealised results of sprinkling experiments. These response curves control the partitioning of rainfall between fast and slow runoff components (e.g. Smoorenburg, 2015). Its parameterisation makes QArea particularly suitable for applications in other catchments, provided that the spatial distribution of DRPs is available. However, the requirement to define the initial conditions in QArea is problematic, and the model is not directly able to exploit spatially distributed information on soil moisture. As an enhancement to QArea, Schmocker-Fackel (2004) developed the event-based model QArea-pro, in which each DRP is represented by a separate module. The runoff calculated for each DRP is then multiplied with the respective area in each sub-catchment. Therefore, both surface and subsurface flows are delayed through a linear storage, to simulate overland and groundwater flow retention, respectively. Surface and subsurface flow is summed for each DRP, and all process flows are summed to yield the total sub-catchment flow. Finally, sub-catchment flows are combined to obtain the total catchment flow. Because the model is event-based, a constant evapotranspiration rate and a factor to account for pre-event soil moisture have to be specified before the start of the simulation. Furthermore, interception losses and flood routing are not included in the model. In addition, the size of a sub-catchment should not exceed 10 km^2, as the linear storage coefficients to calculate runoff concentration are scale dependent.

The model was successfully applied in small Swiss catchments for estimations of the design flood. Recently, Smoorenburg (2015) developed the QArea+ model and applied it in several alpine catchments on the Swiss Alps. The model has a tailored structure for each DRP, but as many parameters as possible are shared between the DRPs to reduce model complexity. The parameters were mainly defined a priori from field observations on the catchments investigated. Simulations of extreme events showed that the model is able to simulate well both flood peaks and volumes.

Blöschl et al. (2008) developed a distributed model for forecasting flash floods in northern Austria. The model structure is similar to that of the HBV model (Bergström, 1976), and the model parameters are identified based on field investigations, runoff data, and piezometric heads of the catchment investigated. With the same model, Rogger et al. (2012) investigated step changes in the empirical distribution of flood peaks in two small Austrian alpine catchments. Kohl and Stepanek (2005) developed the conceptual model ZEMOKOST based on field investigations and sprinkling experiments performed on several locations in Austria. The model is event-based and relies on the calculation of flow times for each DRP class derived with the mapping approach of Markart et al. (2004). These flow times are then summed to get the total hydrograph of the given catchment.

Uhlenbrook et al. (2004) developed the tracer aided catchment distributed (TAC^D) model based on experimental results including tracer studies on the Brugga basin (40 km^2) in Baden-Württemberg (Germany). This raster-based model (50 x 50 m^2) works on an hourly basis and relies on the spatial delineation of DRP units developed by (Tilch et al. (2002). It uses linear and non-linear reservoir modules to conceptualise DRPs. For each grid cell, a DRP is individuated, and a reservoir routine is assigned consequently. Therefore, the water is routed between the cells applying a single-flow direction algorithm (O'Callaghan and Mark, 1984). This defines the model structure with sequentially connected reservoirs. Carver et al. (2009) developed a runoff generation module based on the DRP concept for peak flow hazard modelling of the Fraser basin (British Columbia). The module is based on the definition of a runoff contributing factor for each DRP, which is multiplied with the precipitation input to simulate a daily contribution to the peak flow for each grid cell. Similarly, Rosin (2010) developed one specific combination of runoff generation modules for each DRP to assess effects of land use changes on runoff in ungauged basins. Recently, Steinbrich et al. (2016) developed the RoGeR model for predicting flash-floods in the state of Baden-Württemberg (Germany). The model avoids calibration, but, for the parameter allocation, high-resolution data are needed (e.g. soil maps, hydrogeological maps). Furthermore, the particularly high spatial and temporal resolution of the model reduces its applicability to large mesoscale catchments.

Hellebrand et al. (2011) developed the DRP model, where storages with specific capacities are defined for each DRP. All process modules operate in parallel, and the output of each storage is multiplied with the fraction that its process occupies in the catchment considered, according to the DRP map. Finally, the simulated catchment discharge is calculated by summing the outputs of each single unit, and is convoluted using a triangular transfer function. The storage capacities of the different modules were defined a priori, whereas storage constants were calibrated. The DRP-model was applied on 14 catchments in Luxembourg. However, no clear improvement was found compared with the conceptual FLEX model (Fenicia et al., 2008). Modelling approaches were developed also using the FLEX approach, i.e. a framework for developing tailored model structures making use of e.g. topographic information to distinguish between DRPs (Fenicia et al., 2008; Savenije, 2010). Concerning this model family, a perceptual model is first identified for each DRP; then, a model structure composed by several reservoirs is assigned to each class. For example, Gao et al. (2014) applied the FLEX approach on the Upper Heihe (China). They identified four different landscape units and linked them with DRPs. For each landscape unit, different combinations of storages were defined according to the perception of catchment functioning. These model components run parallel, except for the groundwater storage, which covers the whole catchment. This model, named FLEX-topo, was found to perform better than a lumped and a semi-distributed version of FLEX. In a further example, Gharari et al. (2014) identified three landscape classes for the Wark catchment (Luxembourg). Also in this case, the model components run in parallel, except for the groundwater storage. For each landscape unit, besides the DRP, also other subordinate runoff generation processes are allowed to occur. By imposing semi-quantitative, relational expert-based rules into the model development and parameter selection, they obtained a performance increase for the semi-distributed FLEX-topo, compared to a lumped version of the FLEX model. Also, predictive uncertainty was reduced.

1.4 Research gaps and research questions

Based on the literature study presented above, different research gaps were identified and research questions were formulated accordingly. Concerning the different mapping approaches described above, a direct comparison among them on a given catchment could help to understand to which extent the underlying simplifications and assumptions of each classification method are valid. Meissl et al. (2008) applied some of the classifications described previously (Markart et al., 2004; Schmocker-Fackel et al., 2007; Tilch et al., 2002; Waldenmeyer, 2003) to 23 small basins in the Bavarian Alps. The comparison highlighted the potential of the classification methods for applications in alpine areas. However, problems arose due to applicability limits of the mapping approaches or lack of required data. An important question to investigate is the accuracy in the spatial representation of DRP, which is likely to be poor for methods relying on less input data.

The mapping approaches presented in section 1.3.1 differed from each other in terms of complexity, i.e. the amount of input data needed and DRP classes mapped. There are two underlying philosophies, which focus the expert knowledge in the classification or in the modelling phase, respectively. These philosophies can be seen as different attempts of pursuing the dialogue between modellers and experimentalists to improve the realism of hydrological models (Seibert and McDonnell, 2002). In the first approach, expert knowledge is used to make the spatial distribution of DRPs as realistic as possible, assuming that a more detailed representation of DRP distribution would allow the parameterisation of the DRPs in the model to be simplified. This philosophy underlies the approaches of Qarea-Pro, DRP model and TAC^{D}. In the other case, a relatively complex combination of modules and fluxes is adopted as a consequence of the simplified DRP mapping. Expert knowledge is therefore used to constrain both model fluxes and parameters. This approach reduces field investigations and avoids the use of soil data, at the expense of a detailed spatial localization of DRPs.

Both approaches present critical aspects. On one hand, the use of topographical-based mapping approaches relies on the assumption that topography is closely linked to geology, soil, land use, climate and, therefore, to the DRPs (Savenije, 2010). However, topography is only one factor controlling DRPs and often not the most important one (Beven, 2000; Devito et al., 2005; Meerveld and Weiler, 2008). The biases originated by such simplified mapping approaches could therefore strongly affect simulation results on basins, where other controls dominate. On the other hand, the problematic identification of preferential flow paths in the field, and the impossibility to quantify the lateral flow capacity of soils challenge the distinction between different drainage mechanisms (Hellebrand et al., 2011). This can lead to problems during the upscaling of the results from the field investigations to the catchment scale.

The spatially distributed information on DRPs could be exploited by the model either in a semi-distributed scheme, e.g. Qarea-pro, DRP model or FLEX-TOPO, or in a grid-based one (e.g. LARSIM or TAC^{D}). An important issue linked to the spatial discretisation is the hydrological connectivity, i.e. how an upslope process interacts with a downslope process. The issue of whether there is significant connectivity between neighbouring areas depends on local conditions (Savenije, 2010). For example, Sen et al. (2010) demonstrated that hydrologic connectivity is important for generating runoff when HOF dominates. Connectivity can be considered in both discretization cases, even though different approaches are involved. In a semi-distributed model, connectivity has to be taken into account during the mapping phase. During the manual mapping of DRPs, the influence of neighbouring areas is already considered and can lead to a re-classification of process areas. In this way, a deviation occurs between the local process determined with a GIS-based procedure and the mapped process at the same site. Also, connectivity could be considered in a grid-based model. For example, Rosin (2010) introduced a framework to include connectivity modules in a simplified, spatially distributed model. Using the single-flow direction algorithm (D8), the water is routed solely between cells directly connected to the stream or connected via other stream-connected cells. His findings suggest that the model quality can be improved with these modules. However, high spatial and temporal resolutions are required, which restrict the applicability of the method for larger basins.

The above mentioned research gaps lead to following research questions, which were addressed within the PhD project:

1) To what extent are the assumptions involved in simplified GIS-based mapping approaches acceptable? How do differences in the mapping approaches affect the results of hydrological simulations?

2) How can the information contained in DRP maps be exploited?

3) How does uncertainty in forcing data and in the initial conditions affect simulation results? How does the model setup, i.e. the parameterisation approach and the parameter allocation strategy, affect the results?

2. Material and methods

In the previous chapter, an overview of the mapping and modelling strategies based on the DRP concept was given. Based on this literature study, relevant research gaps were identified and correspondent research questions were formulated. In this chapter, an overview of the material and methods developed and used to address the research questions is given. After a brief description of the study catchments (§2.1), the process maps derived for each of them are presented in §2.2. Therefore, the process-based runoff generation module (RGM-PRO) developed for the PhD project is introduced in §2.3. The meteorological data used to force RGM-PRO, and the runoff data used for its verification are introduced in §2.4, whereas the verification methods are explained in §2.5.

2.1 Study catchments

To address the research questions, several catchments located in Switzerland were investigated (Figure 2.1 and Table 2.1).The Sperbelgraben and the Rappengraben are located close to each other in the Emmental region, Canton Bern. They are similar in terms of area (about 0.5 km^2), geology (Molasse with conglomerate layers), soil type (mainly cambisol) and topography (steep slopes), while they differ considerably in terms of forest coverage. While forest completely covers the Sperbelgraben, only about the half of Rappengraben is covered by forest and the remaining part is used as pasture (Stähli et al., 2011).

The catchment of Dorfbach Meilen (4.6 km^2) and that of the Reppisch up to Birmensdorf (22 km^2) are both located on the Swiss Plateau in the Canton of Zurich. Both catchments are mainly covered by grassland and forest and, to a lesser extent, arable land and settlements, and they are characterised by the Upper Freshwater Molasse with conglomerate in the shallow subsurface (Bolliger, 1999; Hantke, 1967; Pavoni et al., 1992). Cambisols with normal permeability and storage capability cover most of the catchments.

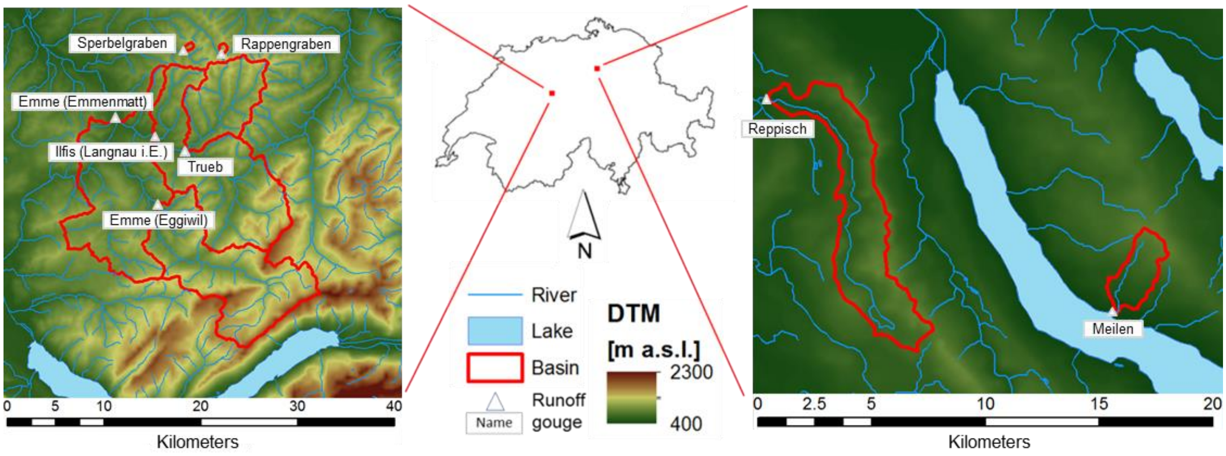


Figure 2.1 Location of the study catchments.

Table 2.1 Overview of the study catchments. F = forest; M = grassland; S = settlements.

Catchment	Area [km²]	Landscape	Elevation [m a.s.l.]	Landuse [%]	Dominant soil type
Sperbelgraben	0.5	Prealps	911 - 1203	100 F	Cambisol
Rappengraben	0.6	Prealps	996 - 1256	54F; 46 G	Cambisol
Dorfbach Meilen	4.6	Swiss Plateau	409 - 850	39 F; 53 G; 8 S	Cambisol
Reppisch	22	Swiss Plateau	467 - 894	48 F; 42 G; 7 S	Cambisol
Trueb	55	Prealps	730 - 1405	56 F; 43 G; 1 S	Cambisol and Regosol[1]
Emme (Eggiwil)	125	Prealps	745 - 2213	59 F; 39 G; 2 S	Cambisol
Ilfis	184	Prealps	685 - 2080	51 F; 47 G;2 S	Cambisol and Regosol[1]
Emme (Emmenmatt)	445	Prealps	638 - 2213	44 F; 52 G; 4 S	Cambisol

[1]According to Scherrer AG (2012).

The Emme catchment up to Emmenmatt (445 km²) is located in the Prealps mainly in the Canton of Bern and, on the eastern side, in the Canton of Lucern. About half of the catchment (52%) is covered by meadow, whereas the remaining part is forested (44%) or covered by settlements (4%). The upper part of the catchment is characterised by Flysch and Cretaceous, whereas Freshwater and Marine Molasse and, to a lesser extent, Moraine dominate the lower part of the basin. Three additional runoff gauging stations can be found in Eggiwil (Emme catchment, 125 km²), Langnau i.E. (Ilfis catchment, 184 km²) and Trubschachen (Trueb catchment, 55 km²), and their measurements were used to evaluate model performances.

2.2 Process maps

In this section, the different mapping approaches used here for deriving process maps are described. Table 2.2 shows, for each study catchment, which process maps were available, and for which study (i.e. paper) they were used.

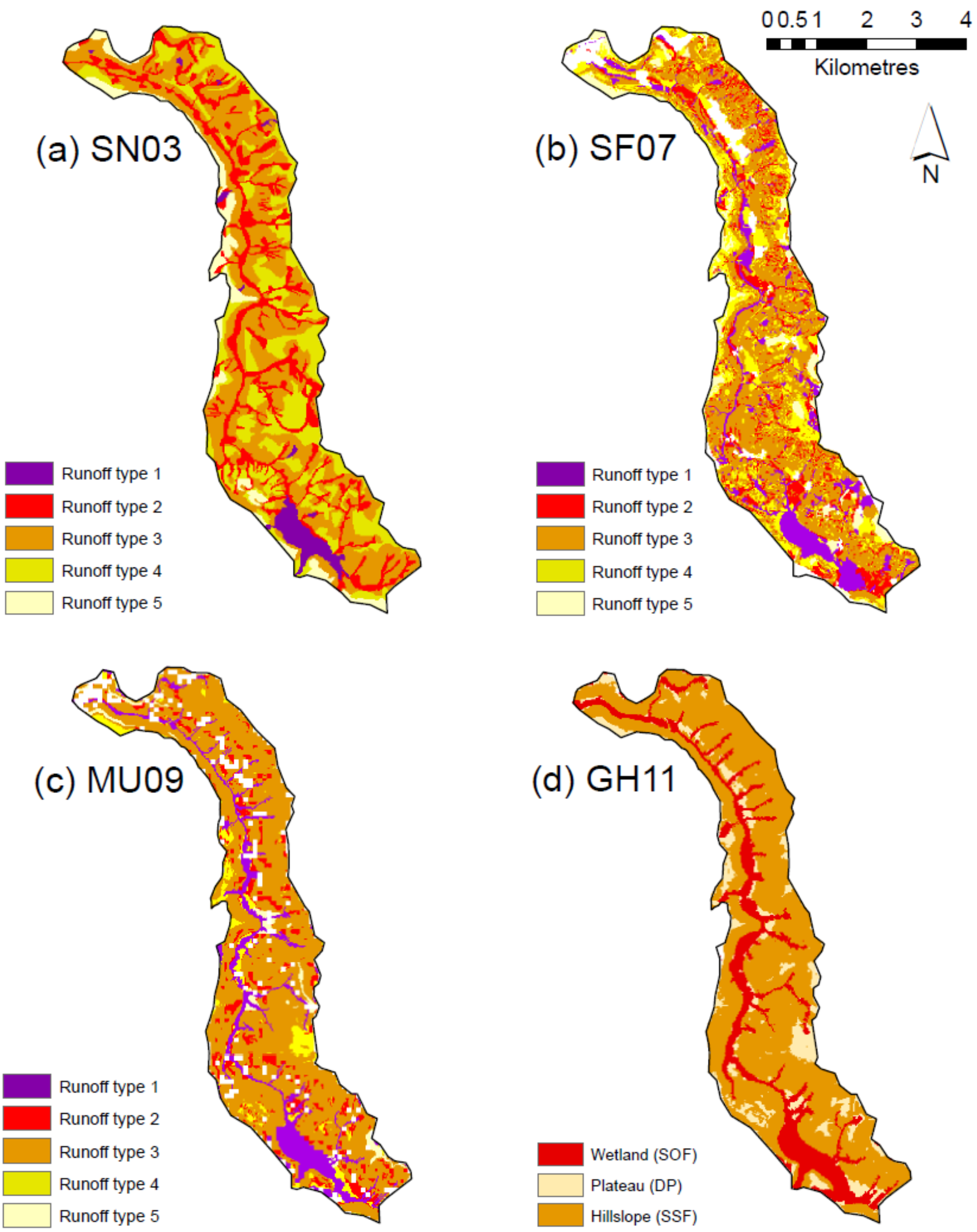


Figure 2.2 Examples of process maps for the Reppisch catchment: (a) manually derived map according to Scherrer and Naef (2003) and automatically derived map according to (b) Schmocker-Fackel et al. (2007), (c) Müller et al. (2009), and (d) Gharari et al. (2011).

Table 2.2 Overview of the process maps available for each catchment study and corresponding research paper.

Catchment	Area [km²]	SN03	SF07	MU09	GH11	Paper
Sperbelgraben	0.5		X			II
Rappengraben	0.6		X			II
Dorfbach Meilen	4.6	X	X	X	X	I & II
Reppisch	22	X	X	X	X	I & II
Trueb	55		X	X	X	III
Emme (Eggiwil)	125		X	X	X	III
Ilfis	184		X	X	X	II & III
Emme (Emmenmatt)	445		X	X	X	III

2.2.1 Manually derived process maps

SN03 maps. Manually derived process maps based on the decision scheme of Scherrer and Naef (2003) are developed in different steps as follows:

1. Information about the land use, vegetation, soil, geology, hydrogeology, and topography of the catchment is collected.
2. Based on these data, the DRPs are initially estimated using expert knowledge, and locations where estimations are not straightforward are identified.
3. On these sites, soil profiles are investigated and the DRP at the plot sites identified according to the decision schemes for long-lasting events, i.e. with precipitation intensity less than ca. 20 mm h^{-1}, of Scherrer AG (2006).
4. After the analysis of the field investigations, the DRPs can be determined for the hillslopes and finally for the whole catchment.
5. The DRPs are reclassified into five different runoff types (RTs) with respect to the runoff intensity (Table 2.3).

These DRP maps, referred to here as SN03 maps, were provided by Scherrer AG for both the Reppisch and Dorfbach Meilen catchments, where they were used as reference maps (Figure 2.2a).

2.2.2 Automatically derived process maps

SF07 maps. Schmocker-Fackel et al. (2007) developed a strategy to simplify the decision schemes of Scherrer and Naef (2003) and determine the DRPs automatically within a GIS environment. The method relies on a soil map with high resolution (1:5000) of the Canton of Zurich and information about the soil water regime, soil depth, and the soil's physical and chemical properties. Where information on soil is lacking, an expert-based soil prediction model was used to derive DRPs from information about forest communities, the slope and shape of hillslopes, the surface water network, and the geology (Margreth et al., 2010). This step is relatively time-consuming, since the soil prediction model has to be adapted to each catchment according to the information available. Therefore, several days of fieldwork are necessary. The approach consists of following steps:

(1) All the available information about a given catchment (topography, land use, vegetation, soil, geology, hydrogeology etc.) is collected and the classification algorithm is adapted to it.

(2) Small test area are identified and manually mapped with the approach described above.

(3) The parameter values of the algorithm are identified by comparing the automatic derived map with that derived manually on the test area.

(4) Locations where estimations are not straightforward are verified with a field survey and possible adjustments are carried out.

(5) Step (4) is reiterated until the process map is considered to be consistent with reality.

The DRP maps derived with this approach for this dissertation were provided by Michael Margreth (Soilcom GmbH), and are referred to hereafter as SF07 maps.

MU09 maps. Müller et al. (2009) proposed a further simplification of Schmocker-Fackel et al.'s (2007) approach based on GIS and valid for long-lasting rainfall events. The method combines information on the permeability of the geological substratum, land use, and slope, but excludes soil information. It results in the same DRP classes as those proposed by Scherrer and Naef (2003), and involves, first, using a DTM analysis to identify classes of slopes; then, classifying the geological substrata of the catchments as either permeable or impermeable; and finally, combining the pre-processed digital data to obtain the DRP. Process maps based on Müller et al. (2009), referred to here as MU09, were derived with a spatial resolution of 25m based on the following assumptions:

(1) Riparian zones, i.e. the spots around the river network, were classified as SOF1;

(2) Settlement areas were not considered as the resolution of the land-use map (100 m) was not high enough to obtain a realistic representation of their spatial distribution.

GH11 maps. As a further simplification, topography-based classifications were developed with the assumption that the topography can be seen as a proxy for the geology, soil, land use, climate and, consequently, DRPs (Savenije, 2010). In addition to traditional topographical descriptors (e.g. elevation, slope, and exposition), these methods are based on the HAND value, which represents, in turn, a rearrangement of the "elevation-above-stream" proposed by Seibert and McGlynn (2005). Gharari et al. (2011) found that the combination between HAND and slope provided the most suitable descriptors for a topography-based classification of DRPs. The mapping approach distinguishes between three landscape classes. Areas below a certain HAND threshold value are called "wetland" (subject to SOF). The remaining regions are further divided into two classes: "hillslope", subject to SSF, and "plateau", subject to DP, depending on whether the slope

Table 2.3 Dependency of the DRP on the slope and permeability of the substratum for grassland, arable land and forest, according to Müller et al. (2009).

Runoff type (RT)	DRP	Runoff intensity
1	HOF1/2, SOF1	Fast
2	SOF2, SSF1	Slightly delayed
3	SSF2	Delayed
4	SOF3, SSF3	Strongly delayed
5	DP	Not contributing

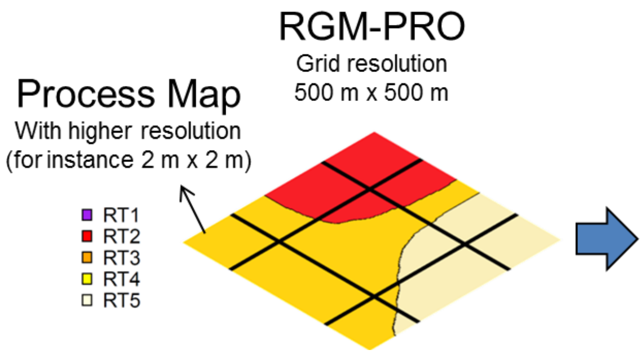
is above or below a certain threshold value. Different combinations of threshold values were tested, and the resulting maps were compared with SN03 at a spatial resolution of 25 m. The maps with the best Mapcurve score (cf. §2.5.1) were used for this dissertation, and are referred to as GH11.

2.3 The PROcess-based Runoff Generation Module RGM-PRO

RGM-PRO is the name of the process-based runoff generation module developed within this dissertation. For its use, information on the spatial distribution of runoff types and spatially distributed forcing data need to be provided. RGM-PRO is event-based, meaning that, for its initialisation, it needs information on the antecedent wetness conditions of the catchment, which could potentially be provided by any grid-based hydrological model or even measured (e.g. Parajka et al., 2005). In the following, the spatial discretisation, the model structure, and the assimilation technique of soil moisture are described. Conversely, the strategies developed for allocating its parameters without the need for calibration are object of paper II and III.

2.3.1 Spatial discretisation

Based on a DTM with a 25 m resolution, each study catchment was divided into sub-catchments up to 2 km^2 in size with the Topographic Analysis Tool (TANALYS; Schulla, 1997). The runoff generation was therefore computed for each sub-catchment. To do this, a grid based discretisation was chosen with a grid size of 500 m × 500 m, and a specific configuration was designed to deal with both the spatial variability of the rainfall data and the spatial heterogeneity of the runoff types. To account for the sub-grid variability of the runoff types, the percentage of each runoff type within each grid cell was first calculated (Figure 2.3). The runoff was then calculated for each cell as if there were one single runoff type for the entire cell. The total runoff was finally calculated as a weighted average. This approach limits computational effort while avoiding information loss due to grid resolution and has already been adopted by Carver et al. (2009) and Nijzink et al. (2016).



Grid Cell	RT1 [%]	RT2 [%]	RT3 [%]	RT4 [%]	RT5 [%]
1	5	0	50	30	15
2	0	17	3	55	25
…					
n	0	2	60	20	18

Figure 2.3 Sketch showing how the sub-grid variability of the RTs is accounted in RGM-PRO.

2.3.2 Structure

The structure of RGM-PRO is based on that of the traditional runoff generation module of PREVAH (Gurtz et al., 2003; Zappa and Gurtz, 2003; Lehning et al., 2006), which follows, in turn, the ideas governing the runoff generation of the HBV model (Bergström, 1976). Concerning the model structure, a specific combination of storages can be defined for each output class of a given hydrological classification (Figure 2.4). The basic structure consists of a plant available soil moisture storage (SSM), a storage system for the runoff generation (SUZ) controlled by four parameters, and a groundwater storage (SLZ; cf. Gurtz et al., 2003; Viviroli et al., 2009a). A non-linearity parameter (BETA) controls the partitioning of rainfall between the plant available soil moisture storage and the runoff generation module. Following Viviroli et al. (2009c), the BETA parameter has been fixed here at the value of 3. In SUZ, the storage times for overland flow (K0H) and subsurface flow (K1H) regulate the generation of the runoff. A threshold (SGRLUZ) determines the separation between overland and subsurface flow, whereas a maximum percolation rate (CPERC) controls the percolation to the groundwater storage. This is divided into a quick-leaking and two slow-leaking storages and controlled by three parameters (SLZ1MAX, CG1H, and K2H). For a more detailed description of the groundwater storage system we refer to Viviroli et al. (2009b) and Schwarze et al. (1999). This basic structure can then be adapted according to the features of the output classes of a given hydrological classification.

2.3.3 Assimilation and downscaling of soil moisture

One of the problems of event-based models is the definition of initial conditions. For the studies presented in this dissertation, the plant available soil moisture was assimilated from grid-based simulations of PREVAH with a resolution of 500 m. These simulations have been computed in real-time since 2012 for the whole of Switzerland as part of the http://www.drought.ch platform (Zappa et al., 2014). Because the spatial variability of the soil moisture is higher than the resolution of the PREVAH simulations, the downscaling technique described in Blöschl et al. (2009) was applied (Figure 2.5).

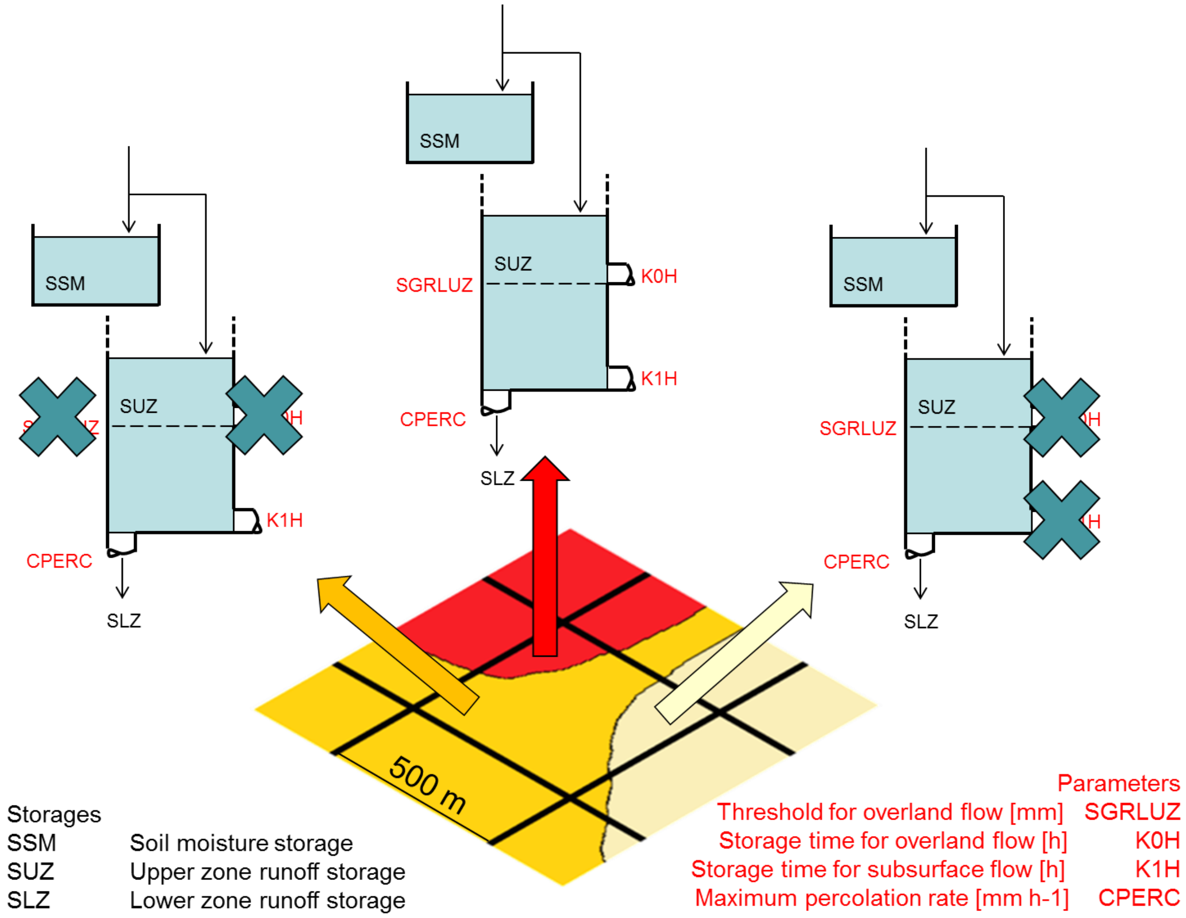


Figure 2.4 Schematic representation of the spatial discretisation and structure of RGM-PRO. For each class of a given process map, a specific storage system can be defined.

This method relies on three basic assumptions:

- The soil moisture pattern at the smaller scale is time invariant;
- The spatial variance of soil moisture at the smaller scale is linked with that at the larger scale by a scaling theory;
- Soil moisture is mass conserving.

The first assumption allows a static pattern (called fingerprint) to be used. As the process maps already include information about the spatial distribution of soil moisture, they were used as fingerprints for this dissertation (Scherrer et al., 2007). As a consequence of the second assumption, the spatial variance of soil moisture at the smaller scale (σ_S^2) was linked to that at the larger scale (σ_L^2) based on following scaling theory:

$$\sigma_S^2 = \sigma_L^2 \cdot \left(\frac{L_S}{L_L}\right)^{-\alpha} \qquad \text{Eq. 2.1}$$

where L_S and L_R are the length scales (i.e. the grid sizes) and α is an empirical exponent set equal to 0.35 according to Blöschl et al. (2009). Owing to the last assumption, the mean soil moisture at the smaller scale was forced to be equal to the mean soil moisture at the larger scale. After the soil moisture was downscaled to a resolution of 25 m, it was successively re-aggregated to obtain an averaged value for each runoff type for each grid cell.

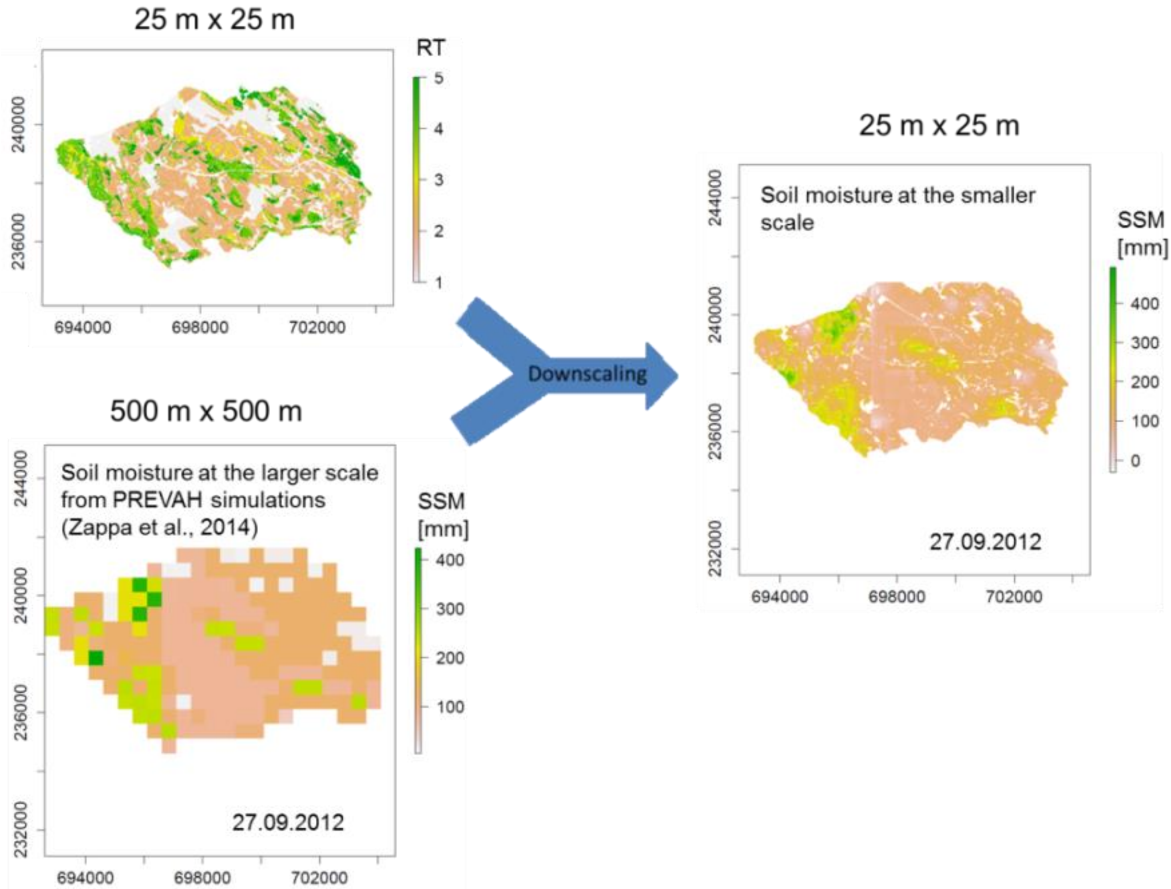


Figure 2.5 Sketch of the downscaling strategy used in our study.

2.4 Meteorological and runoff data

The studies included in this dissertation evaluate the performance and applicability of process-based hydrological modelling approaches forced with precipitation input data derived from weather radars and ground stations. The different precipitation products and the meteorological data used in this dissertation are described in the following paragraphs, whereas the simulated events are listed in Table 2.4 and Table 2.5. According to the flood type classification of Sikorska et al. (2015), nearly half of them can be classified as short-duration events, and the remaining as long-duration events.

Combiprecip. The Combiprecip product (Sideris et al., 2014) is a combination between ground measurements and radar quantitative estimations of precipitation based on a co-kriging with external drift. The method allows both spatial and temporal information to be incorporated into the estimation process. Sideris et al. (2014) show that skill scores improve when the aggregation period of Combiprecip increases from ten minutes to one hour, and they attribute this improvement to the increase in robustness of the input data with increasing period of aggregation. To investigate the interaction between expert knowledge and quality of forcing data (cp. paper III), different spatial aggregations of Combiprecip were introduced. First, for each time step, the average precipitation intensity was distributed all over the main basin (CPC.mean). In a further configuration

Table 2.4 Start and end of the events simulated in Emme, Ilfis, Trueb, Sperbelgraben and Rappengraben.

Name	Simulation start	Simulation end	Event type according to Sikorska et al. (2015)	Paper
Aug05	01.08.2005	31.08.2005	Long-duration	II and III
Sep06	15.09.2006	30.09.2006	Short-duration	II
Aug07	18.07.2007	17.08.2007	Short-duration	II
Aug10	20.07.2010	09.08.2010	Short-duration	II and III
Jun12	01.06.2012	20.06.2012	Long-duration	II and III
Sep12	23.08.2012	18.09.2012	Short-duration	II and III
Aug14	21.07.2014	20.08.2014	Short-duration	II and III
May16	11.05.2016	18.05.2016	Long-duration	II and III

Table 2.5 Start and end of the events simulated in the Reppisch and Dorfbach Meilen catchments.

Name	Simulation start	Simulation end	Event type according to Sikorska et al. (2015)	Paper
Aug05	01.08.2005	31.08.2005	Long-duration	II
Jun13	30.05.2013	14.06.2013	Long-duration	II
Jul14	09.07.2014	16.07.2014	Long-duration	I and II
Jun15	14.06.2015	17.06.2015	Short-duration	II
Jun16	08.06.2016	23.06.2016	Short-duration	II

(CPC.mean.subc), the average precipitation intensity was calculated for and assigned to the corresponding sub-catchment. Finally, the Combiprecip data were used directly as they were delivered by MeteoSwiss.

Ground meteorological stations. To investigate the interaction between expert knowledge and quality of forcing data (paper III), precipitation data from five automatic stations within or close to the basin with a hourly resolution were interpolated based on Thiessen polygons (Thiessen, 1911) and following an Inverse Distance Weighting (IDW; Isaaks and Srivastava, 1989) method with power parameter p set equal to 2.

Measured runoff data. Concerning the measured runoff data, the time series were mainly provided by the Swiss Federal Office for the Environment (FOEN). An exception to this is represented by the Trueb catchment, as the corresponding measured runoff data were provided by the Canton of Bern, whereas the Canton of Zurich provided data for both Reppisch and Dorfbach Meilen catchments. Hourly aggregations of runoff data were used for verification purposes.

2.5 Verification methods

2.5.1 Map comparison

To test the suitability of different approaches for automatically mapping the DRPs on a given catchment, several verification methods were applied. As reference maps, the process maps obtained with the Scherrer AG's (2006) approach were used.

- **Class comparison and deviation map.** The percentage of total catchment area assigned to each runoff type, and the percentages of discrepancy between the runoff types in the compared maps and those in the reference maps were calculated. In addition, the discrepancies between compared and reference maps were highlighted in a deviation map to identify the spots where the difference in the runoff types is greater than two and to help identify the possible causes of incorrect mapping.

- **Fuzzy kappa**. To account for fuzziness in the definition of the runoff types, a measure of agreement, fuzzy kappa (K_{Fuzzy}), was used. The method was proposed by Hagen-Zanker (2009) to take into account the *fuzziness of categories*, allowing some pairs of classes to be more similar than others, as well as the *fuzziness of location*, given that cells tend to be at least slightly spatially correlated. To take the fuzziness of categories into account, a similarity matrix is defined, where each pair of classes is assigned a number between 0 (totally distinct) and 1 (completely identical). The extent to which neighbouring cells influence the cell in question is defined by a distance decay function. An overall measure of similarity between two maps can be obtained by using the following equation:

  $$K_{Fuzzy} = \frac{P-E}{1-E}\ [-] \qquad \text{Eq. 2.2}$$

  where P represents the mean agreement of the two compared maps weighted by the expected agreement E. K_{Fuzzy} ranges from 0 (fully distinct maps) to 1 (fully identical maps). For this thesis, the fuzzy kappa algorithm implemented in the Map Comparison Kit 3 software (Visser and De Nijs, 2006) was used.

- **Mapcurves.** Because the number of classes in the process maps can differ from that in the reference maps, the goodness-of-fit (GOF) measure called Mapcurves (Hargrove et al., 2006) was used to quantify the degree of spatial concordance between the automatically derived and the reference maps. For each of the existing classes in two maps, a GOF score was calculated according to the following equation:

  $$GOF_X = \sum_{Y=1}^{n}\left(\frac{C}{A}\cdot\frac{C}{B}\right)[-] \qquad \text{Eq. 2.3}$$

  where A is the total area (m^2) of a given class X on the map being compared, B is the total area (m^2) of a class Y on the reference map, C is the intersecting area (m^2) between X and Y when the maps are overlaid, and n is the total number of classes on the reference map. The sum of this product gives a GOF value for a particular class. The overall Mapcurves (MC) score is given by the area under the curve obtained by plotting the GOF scores on the abscissa and the percentage of map classes with a GOF score larger than a particular value on the ordinate. An MC score of 1 represents a perfect fit, while an MC score of 0 means that there is no spatial overlap between the classes of two maps. MC scores differ when the compared map is used as a reference map. This is because the MC score depends on the average size and number of the patches in each class of the maps being compared. Hargrove et al. (2006) argue that the combination of compared map and reference map that has the highest MC score must be chosen. However, by doing so, the coarser maps would be advantaged. Therefore, for this study, SN03 maps were always set as reference maps.

2.5.2 Hydrograph comparison

Hydrological simulations are evaluated with the following objective functions.

- **Nash Sutcliffe Efficiency NSE.** The efficiency measure proposed by Nash and Sutcliffe (1970) is the most widespread metric in the hydrological community and consists of a dimensionless transformation of the sum of squared errors.

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_{i,obs}-Q_{i,sim}\right)^2}{\sum_{i=1}^{n}\left(Q_{i,obs}-\overline{Q_{obs}}\right)^2} \quad [-] \qquad \text{Eq. 2.4}$$

- As errors in high flows are more amplified than errors in low flow conditions, the NSE is suitable for studies focussing on high discharges. A modified version of the NSE, in which the observed runoff is replaced by the runoff simulated with the reference maps, was used to address the first research question of this thesis (cf. paper I);

- **Kling Gupta Efficiency KGE.** Because the traditional NSE does not give exhaustive information about the error nature, the Kling Gupta Efficiency (KGE, Gupta et al., 2009a) was used in paper II and III:

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2} \quad [-] \qquad \text{Eq. 2.5}$$

  where r represents the correlation between simulated and measured runoff, α is the ratio between the standard deviation of the simulated runoff and that of the measured runoff, and β is the ratio of the mean simulated to mean observed discharge.

- **Root mean squared error RMSE.** When response curves instead of hydrographs are used for the optimisation, the root mean square error (RMSE) was used as objective function:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Q_{i,obs} - Q_{i,sim}\right)^2} \quad [-] \qquad \text{Eq. 2.6}$$

In addition to the above mentioned objective functions, the **Series Distance** (Ehret and Zehe, 2011) method was used to evaluate the temporal and volumetric shift between simulated and measured hydrographs. Series Distance allows simulations to be evaluated as in a visual inspection, as point pairs with similar hydrological meaning (e.g. beginning, peak and end of an event) and not point pairs belonging to the same time-step are compared.

Furthermore, to quantify potential overconfidence problems of the model setups, two factors were calculated, i.e. the **P-factor** and the **R-factor** (Abbaspour et al., 2009). The P-factor is the fraction of measured runoff enveloped by the uncertainty band originated by the different simulation runs, whereas the R-factor is the average width of the uncertainty band divided by the standard deviation of the measured runoff. Ideally, P-factor is equal to 1, meaning that the observed hydrograph is bracketed by the model parameter uncertainty, whereas R-factor tends to zero, i.e. the simulation has the smallest uncertainty band.

Finally, to investigate which uncertainty source contributes most to the total predictive uncertainty, an analysis of variance (**ANOVA**) was carried out. The method is based on the assumption that the uncertainty of an environmental system can be explained by the output variance generated by different uncertainty sources called effects. The method was already used, for instance, to assess uncertainty in climate impact projections (Addor et al., 2014; Bosshard et al., 2013; Köplin et al., 2013) and in agro-hydrological applications (Moreau et al., 2013). Assuming that each effect affects the variability of the simulation performance ΔR_{eff}, following effect model can be defined:

$$\Delta R_{eff} = \overline{R_{eff}} + A_a + B_b + \cdots + N_n + I_{ab\ldots n} + \varepsilon_{ab\ldots n} \qquad \text{Eq. 2.7}$$

Where $\overline{R_{eff}}$ represents the mean performance of the model, A_a, B_b, … N_n are the main effects, i.e. uncertainty sources (e.g. input data, initial conditions, process maps, model structure, model parameter etc.). $I_{ab\ldots n}$ and $\varepsilon_{ab\ldots n}$ represent the interactions between the main factors and the residual error, respectively. Each effect is proofed for its representativeness and only those with a p-value lower than 0.05 are taken into account (Chambers et al., 1992).

3. Overview of papers

In this chapter, the research questions and corresponding main findings of each study performed within this PhD project are presented (Figure 3.1). The first study on the comparison of different process maps is briefly presented in §3.1. The study on the process-based runoff generation module developed within this thesis is summarised in §3.2. Finally, the comparison of different strategies for integrating expert knowledge in conceptual models based on the DRP concept is outlined in §3.3.

3.1 Comparison of process maps

For this study, DRP-maps were produced for two catchments on the Swiss Plateau using the automatic approaches of Schmocker-Fackel et al. (2007), Müller et al. (2009) and Gharari et al. (2011). These were then compared with reference maps produced using manual mapping according to Scherrer and Naef (2003). The objective of the comparison was to: (i) test the suitability of different automatic DRP-mapping approaches for mapping ungauged catchments, and (ii) quantify the uncertainty of hydrological simulations due to different spatial representations of DRPs. To assess the similarity between the automatically derived DRP-maps and the reference maps, a measurement of agreement (Fuzzy Kappa), a measurement of association (Mapcurves), and a class comparison were carried out. Furthermore, the effects of the differences among the DRP-maps on synthetic runoff simulations were investigated with an adapted version of the well-established PREVAH model.

Results showed that the DRP maps derived with the automatic approach with highest complexity and data requirement were the most similar to the reference maps. Conversely, the runoff simulations derived from the simpler DRP maps were more uncertain due to inaccuracies in the input data, but problems were also linked with the use of topography as a proxy for the storage capacity of soils (Table 3.1; Figure 3.2).

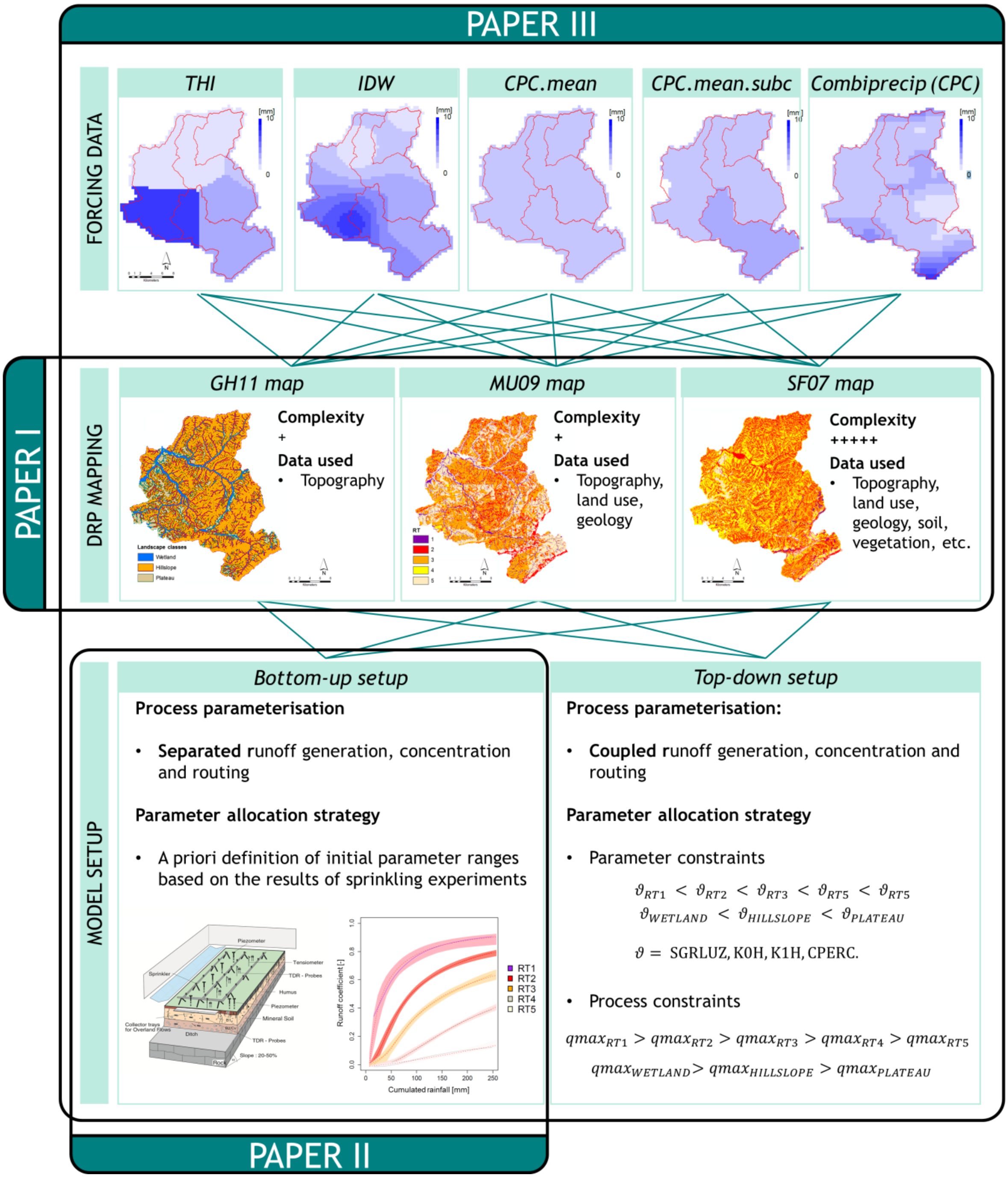


Figure 3.1 Overview of the studies performed during the PhD project. A comparison of different approaches for mapping dominant runoff processes (DRP) was carried out for paper I. A process-based, bottom-up strategy for implementing knowledge on DRPs in a conceptual runoff generation module (RGM-PRO) was developed in paper II. Finally, in paper III, different approaches were compared to investigate whether expert knowledge can increase the model realism even under uncertainty.

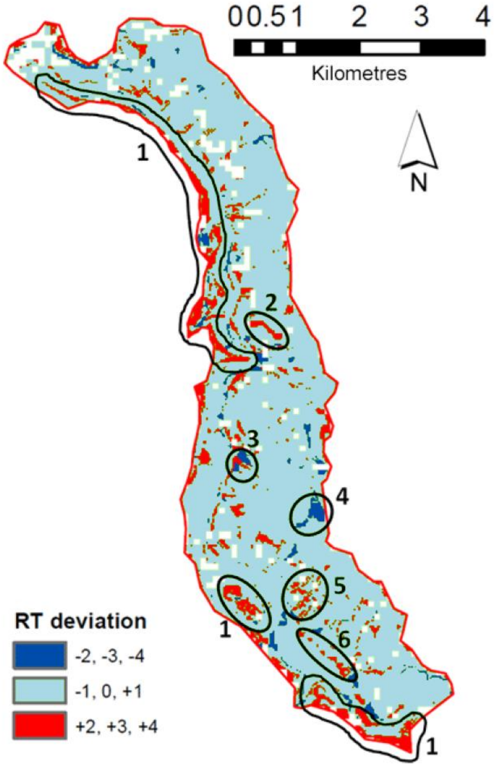


Figure 3.2 Deviation map between the MU09 map and the reference map. In the numbered areas the runoff contribution was either overestimated (red) or underestimated (blue). RT = runoff type. (from paper I)

Table 3.1 List of areas identified in Figure 3.2 with the automatically (MU09) and manually (SN03) derived runoff types, and a possible explanation for their deviation. DRP = dominant runoff process; RT = runoff type. (from paper I)

Area	DRP (RT) on MU09 map	DRP (RT) on SN03 map	Explanation
1	SSF2 (RT3)	DP (RT5)	Moraine not necessarily impermeable
2	SSF1 (RT2)	SSF3 (RT4)	Although high slope, high storage capacity of soil
3	DP (RT5)	SSF2 (RT3)	Alluvium not necessarily permeable
4	SOF3 (RT4)	SOF2 (RT2)	Although low slope, low storage capacity of soil
5	SOF1 (RT1)	SSF2 (RT3)	Coarse resolution of DTM
6	SOF1 (RT1)	SSF2 (RT3)	Coarse resolution of land-use map

This study is published in Hydrological Earth System Sciences under the reference:

Antonetti, M., Buss, R., Scherrer, S., Margreth, M., and Zappa, M.. 2016. Mapping dominant runoff processes: an evaluation of different approaches using similarity measures and synthetic runoff simulations. *Hydrology and Earth System Sciences* 20 (7): 2929–2945 DOI: 10.5194/hess-20-2929-2016

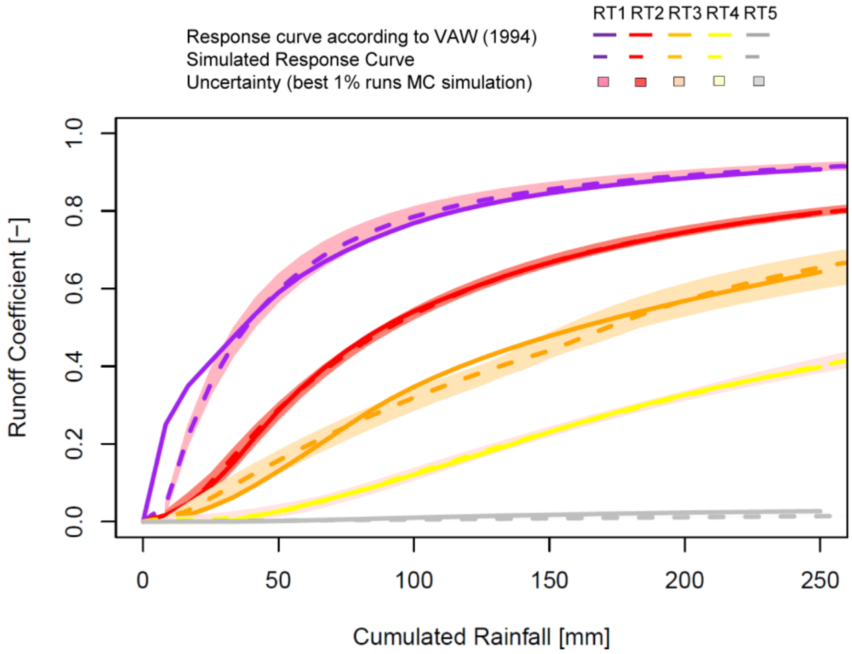


Figure 3.3 Simulated response curves and hydrographs for the five runoff types (RTs). (from paper II)

3.2 The process-based runoff generation module RGM-PRO

In this study, RGM-PRO, a process-based spin-off of the runoff generation module of PREVAH, is introduced. Four strategies for the allocation of its parameters were developed based on the results of sprinkling experiments, and the best one was used to compare the results of RGM-PRO with those of different configurations of the traditional conceptual runoff generation module of PREVAH on several catchments.

Allocating parameters based on generalised response curves for each runoff type allowed subordinate processes, heterogeneities and the process catena on the hillslope to be taken into account (Figure 3.3). This parameter allocation strategy led to the best performances on the study catchments. RGM-PRO allowed the spatial representation of runoff within the catchment to be more realistic without decreasing the model performance. Also, simulation results of RGM-PRO were better than those obtained with other typical regionalisation techniques based on either parameter transfer or parameter regionalisation in both temporal and volumetric terms. Therefore, including information on the spatial distribution of runoff types in a conceptual hydrological model is a feasible technique for (i) performing hydrological simulations on ungauged catchments and (ii) increasing model realism without resorting to the use of calibration.

This paper is accepted for publication in Hydrological Processes under the reference:

Antonetti, M., Scherrer, S., Kienzler, P. M., Margreth, M. and Zappa, M.. 2017. Process-based hydrological modelling: the potential of a bottom-up approach for runoff predictions in ungauged catchments. *Accepted for publication in Hydrological Processes*. DOI: 10.1002/hyp.11232

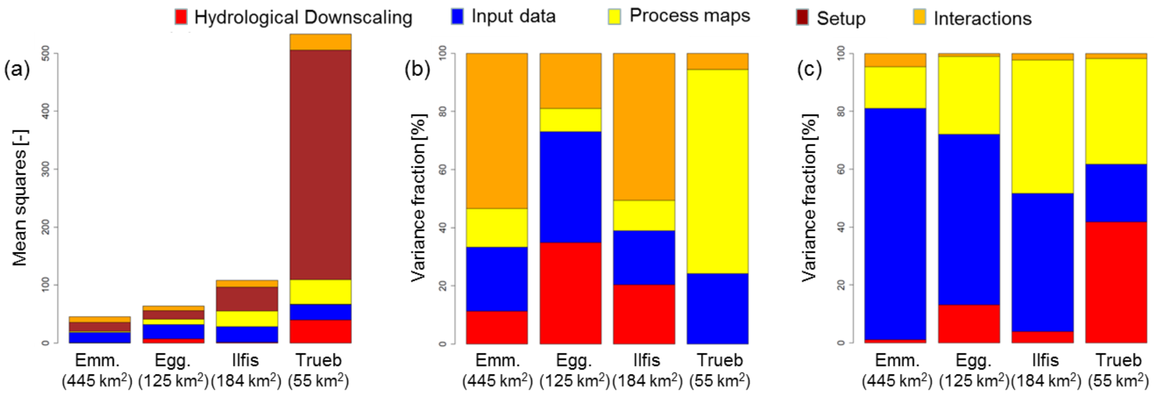


Figure 3.4 Decomposition of the model performance (KGE) variance at the four gauging stations for all the modelling chain combinations (a), as well as for those based on the bottom-up (b), and top-down (c) setups. (from paper III)

3.3 Comparison of different strategies for implementing expert knowledge in hydrological conceptual models

For this study, process maps of a mesoscale catchment on the Swiss Pre-Alps were derived using three mapping approaches with different involvement of expert knowledge. The effects of the differences between the process maps on runoff simulations were investigated with two different setups of the newly developed RGM-PRO: a typical modellers' top-down setup relying on parameter and process constraints, and an experimentalists' setup based on bottom-up thinking and field expertise (Figure 3.1). Both setups were forced with input data of different accuracy. Finally, an analysis of variance was performed to quantify the uncertainty originated by input data, process maps, model parameterisation and parameter allocation strategy. Following issues were investigated: (i) Does the use of more expert knowledge during the mapping phase improve hydrological simulations? (ii) For which conditions (event type, catchment characteristics) can satisfying results be reached even with low involvement of expert knowledge during the mapping phase? (iii) How does uncertainty in forcing data and in the initial conditions influence the simulation results? (iv) How does the model setup, i.e. the parameterisation approach and the parameter allocation strategy, affect the results?

The main findings of the study are the following: (i) The potential added value of complex process maps with high involvement of expert knowledge is severely restricted by large uncertainties, even in the best forcing data available in real-time and in the measured discharge data. (ii) Satisfying performances were reached also with simplified mapping approaches, especially for long-lasting events. (iii) The uncertainty linked with the process maps and, consequently, the importance of a realistic representation of the spatial distribution of DRPs, increased with the decrease in size of the catchments (Figure 3.4). (iv) The bottom-up setup developed for paper II reached on average better performances than the top-down setup on the investigated catchment.

This paper is under review for Hydrological Earth System Sciences under the reference:

Antonetti, M. and Zappa, M.: How can expert knowledge increase the realism of conceptual hydrological models? A case study in the Swiss Pre-Alps, in review, 2017. Hydrol. Earth Syst. Sci. Discuss. DOI: 10.5194/hess-2017-322

4. Discussion

In this chapter, the results of the three studies carried out within this dissertation are synthesised and briefly discussed. The first part addresses the comparison of the different DRP mapping approaches, whereas the second one deals with the modelling strategies developed.

4.1 Comparison of process maps

One of the purposes of this dissertation was to test how well automatic approaches can map small catchments. This research question was investigated by using similarity measures first (paper I). The most complex automatic process maps (Schmocker-Fackel et al., 2007) proved to be most similar to the reference maps derived manually, according to both the class comparison and the similarities measures. This result is not surprising, considering that Schmocker-Fackel et al.'s (2007) mapping approach was developed on the canton of Zurich, where the two study sites of paper I are located. However, the method was successfully tested also outside the canton of Zurich, e.g. on the Swiss Pre-Alps (Scherrer AG, 2012). Conversely, the DRP-maps derived with simplified mapping approaches, that included no soil information, differed significantly from the reference maps in terms of both extent and distribution of the DRPs. These differences are clearly linked to the quality of the input data. However, using input data with high resolution would not necessarily improve the results, if the classification concept itself is too coarse and generic. As topography does not seem to be a good proxy for the storage and infiltration capacity of the soils on the study sites, the mapping approaches developed by Müller et al. (2009) and Gharari et al. (2011) often overestimated the runoff intensity on steep sites and underestimated it on flat sites.

The effect of the differences in the mapping approaches on the results of hydrological simulations was investigated in both papers I and III. In paper I, the same conditions (i.e. model structure and constraints) were applied to the different DRP-mapping approaches to focus exclusively on a precise uncertainty source, i.e. the DRP-maps, while keeping fixed the other uncertainty sources. This led to the conclusion that it is worthwhile investing efforts and using expert knowledge to obtain hydrological landscape classifications that are as realistic as possible. In paper III, all the uncertainty sources (input data, model structures, model parameters, and model constraints), as well as their interactions, were considered. This showed how the potential added value of complex process maps with high involvement of expert knowledge can be severely restricted by large uncertainties even in the best forcing data available in real-time and in the measured discharge data. As a consequence, performance using simplified mapping approaches was also satisfactory, especially for long-duration events. This is possibly linked with the fact that, over the years, instead of refining the process maps by drawing on more knowledge in the mapping phase, the opposite occurred, and the uncertainty in the input data was used as an excuse for removing complexity from hydrological classifications. For example, Müller et al. (2009) developed their mapping approach based exclusively on information about topography, geology, and land use in order to simplify the method of Schmocker-Fackel et al. (2007), which is in turn a simplification of the manual mapping approach developed by Scherrer and Naef (2003) and is based on all the information available about a basin. Only two years later, Gharari et al. (2011) introduced their classification approach based exclusively on topography.

The finding of paper III seems to contradict what was found in paper I. However, it is not acceptable from an experimentalist point of view, as the results may seem acceptable at the gauging stations, but the local representation of the DRP mapped would most likely differ from that expected by an experimentalist. Modellers and experimentalists need therefore to agree on what they mean by "model realism", and how much detail hydrologists should provide to achieve it. An exact reproduction of processes at the plot scale (e.g. exact localisation of macropores etc.) is of course unfeasible due to lack of data, and even knowledge, and the high computational effort such a level of detail would require (Beven, 2001, 2000; Semenova and Beven, 2015; Weiler and McDonnell, 2004). No experimentalist would therefore expect this level of detail from a process-based model at the catchment scale. However, the hydrological community should aspire to develop models able to reproduce processes in a "realistic" way (i.e. in agreement with the experimentalists' expectation), at least at the sub-catchment or, even better, at the hillslope scale. This should be a feasible goal, especially considering how new measurements techniques continue to be developed and existing ones refined (Savenije and Hrachowitz, 2017). Such high requirements will probably challenge the validity of simplified mapping approaches and highlight the added value of the more complex ones.

4.2 The process-based runoff generation module

The main goal of this dissertation was to develop an approach for exploiting information contained in DRP maps. This was pursued stepwise. In paper I, strong assumptions had to be made to keep the model as simple as possible. These included no interception, no evapotranspiration and completely saturated catchments. Especially due to this last assumption, a calibration against measured runoff would have been meaningless, and this is why “synthetic” (i.e. virtual) runoff simulations were performed. However, the choice of realistic parameter values according to Viviroli et al. (2009a) and the introduction of parameter constraints allowed the results obtained from the synthetic simulations to be plausible.

The real approach for the integration of expert knowledge within a hydrological model was presented in paper II. The model was further developed by adding a storage for the soil moisture, and by introducing the sub-grid parameterisation of DRPs. The resulting configuration was named PROcess-based Runoff Generation Module - RGM-PRO. The model was able to simulate both overland and subsurface flow of several sprinkling experiments performed during previous investigations (Kienzler, 2007; Scherrer, 1997). Other studies reached similar results, but with computationally highly demanding models (Faeh et al., 1997a; Steinbrich et al., 2016). Not surprisingly, the same parameter ranges used for simulating the sprinkling experiments did not lead to satisfying results when applied on larger catchments. This was mainly due to two factors, the first one linked to overfitting problems, the second one linked with the concept of “uniqueness of place” (Beven, 2002, 2000). In contrast, defining a priori plausible parameter ranges, and optimising them against idealised response curves for each class of a process map, has been proved to be a promising and straightforward technique for the application of RGM-PRO at the catchment scale. A similar parameter allocation strategy is already implemented in the QAREA model family (Horat, 2000; Smoorenburg, 2015; VAW, 1994). With the approach presented in paper II, however, the initialisation problems of QAREA mentioned in the introduction (§1.3.2) have been removed, and any spatially distributed soil moisture data can be used to initialise RGM-PRO.

The bottom-up modelling approach presented in paper II can be therefore seen as a successful attempt to bridge the gap between experimentalists and modellers (Seibert and McDonnell, 2002). It represents a framework for the use of all detailed and qualitative knowledge about processes obtained by experimentalists. This knowledge is first used during the phase of mapping the landscape, and, second, during the parameter allocation phase when plausible ranges are defined for each model parameter. The very same bottom-up approach has proven to be valuable as a regionalisation technique, given that it improved the simulation of the hydrographs in both temporal and volumetric terms.and has advantages over other two regionalisation techniques used in paper II (i.e. the transfer in space and time of calibrated parameters, and the usage of regionalised parameter values), also in terms of robustness and transferability.

In paper III, a further model setup based on modellers’ top-down thinking was introduced. The main differences with the bottom-up one developed in paper II lie in the parameterisation of runoff generation, runoff concentration, and routing (coupled in the top-down, uncoupled in the bottom-up setup, see Figure 3.1), and in the parameter allocation strategy. The low performances of the top-down setup in simulating the short-duration events probably depended on the coupled parameterisation of runoff generation, concentration, and routing. As fast subsurface flow is basically not allowed to occur, the reaction to high precipitation intensity was found to be insufficiently fast. With regard to the bottom-up parameterisation, the observed underestimation of the falling limb of the hydrograph was ascribable to the poor representation of the runoff concentration by the bottom-up setup. Concerning the parameter allocation strategies, the very same low performances reached by the top-down setup during short-duration events could be also related to the modellers' tendency to set relational rules among parameter and fluxes of different classes (Gharari et al., 2014). Although the definition of parameter and process constraints force the model to behave according to the modeller's perception of the catchment functioning, the parameter space defined by the initial parameter ranges used in paper III (Viviroli et al., 2009b) was apparently still too large to ensure high performances with only 100 Monte Carlo runs. On the other hand, the bottom-up parameter allocation strategy led to overconfidence problems, as the measured runoff was only partially enveloped by the uncertainty bands defined by the different runs of the Monte Carlo simulation.

Considering the KGE deviations arising from the use of different forcing data delivered further insights into the model setups tested here. The lower KGE deviations observed for the top-down setup showed that it can cope better than the bottom-up setup with uncertainties in the input data, as it allows parameter values that can compensate for biases in the input data to be selected. This also explains the larger performance spreads reached by the modelling chains based on the top-down setup, as not all the parameter sets fulfil the requirements for compensating a biased forcing. The bottom-up setup is therefore suitable for identifying uncertainty sources. Once the extent and distribution of DRPs on a given catchment corresponds to the experimentalist's perception, which may still be biased, and once, for each output class of a process map, a proper parameterisation has been chosen, any remaining deviations of the simulated hydrograph from the measured hydrograph can be explained as arising from uncertainties either in the forcing data or in the measured discharge data.

5. Conclusions

The aim of this PhD project was to improve hydrological simulations by developing a strategy for exploiting information on the spatial distribution of dominant runoff processes (DRPs) from so-called DRP-maps (or process maps). With regard to the research questions stated in §1.4, the following conclusions can be drawn:

1) *To what extent are the assumptions involved in simplified GIS-based mapping approaches acceptable? How do differences in the mapping approaches affect the results of hydrological simulations?*

- The DRP maps produced using simplified mapping approaches, which require no soil information, differed considerably and similarly from the reference maps in terms of DRP extent and distribution. Such differences arose from the inaccuracy and the coarse resolution of the input data, but the simplifying assumptions these two approaches require also limit their usefulness in automatically mapping small catchments. Synthetic runoff simulations performed with these simplified DRP maps significantly differed from those performed with the reference maps. This suggests that it would be worthwhile investing efforts and using expert knowledge to obtain hydrological landscape classifications that are as realistic as possible.

2) *How can the information contained in DRP maps be exploited?*

- Information on DRPs was exploited by developing an event-based runoff generation module (RGM-PRO) which allows a tailored model structure to be defined for each process. RGM-PRO was fed with hourly grid-based precipitation data, while information on the soil moisture was assimilated and downscaled from continuous simulations of PREVAH. Its parameter values were allocated based on generalised response curves derived from sprinkling experiments. These allowed subordinate processes, heterogeneities and the process catena on the hillslope to be taken into account.

- Compared with a traditional, conceptual runoff generation module, RGM-PRO allows the spatial representation of runoff within the catchment to be more realistic without decreasing the model performance. Also, simulation results of RGM-PRO were better than those obtained with other typical regionalisation techniques based on either parameter transfer or parameter regionalisation in both temporal and volumetric terms. This suggests that including information on the spatial distribution of dominant runoff processes in a conceptual hydrological model is a feasible technique for performing hydrological simulations on ungauged catchments without resorting to the use of calibration.

3) *How does uncertainty in forcing data and in the initial conditions affect simulation results? How does the model setup, i.e. the parameterisation approach and the a priori parameter allocation strategy, affect the results?*

To answer these questions different approaches for using expert knowledge in hydrological models were compared. In a first place, the influence of different degrees of expert knowledge applied for landscape classification on the final outcome of hydrological simulations was investigated. Two different setups (i.e. parameterisation and parameter allocation strategies) were compared, the one based on an (bottom-up) experimentalists' reasoning, the other driven by a (top-down) modellers' thinking. The performance variation due to the use of forcing data with a higher uncertainty degree was investigated, and the fraction of variance explained by each uncertainty source (i.e. input data, initial saturation conditions, process maps, model parameterisation, and parameter allocation strategy) was quantified. The main findings are following:

- The potential added value of complex process maps with high involvement of expert knowledge is severely restricted by large uncertainties even in the best forcing data available in real-time and in the measured discharge data. Satisfying performances were also reached with simplified mapping approaches, especially for long-lasting events.

- On the investigated catchment, the model setup based on an (bottom-up) experimentalists' reasoning reached, on average, better performances than the one driven by a (top-down) modellers' thinking, independently from the process map used. The bottom-up setup can be used as a diagnostic tool to identify the uncertainty sources, but showed considerably overconfidence problems due to a too narrow a priori definition of parameter ranges.

- The uncertainty linked with the process maps and, consequently, the importance of a realistic representation of the spatial distribution of processes, increased with the decrease in size of the catchments.

6. Outlook

The following chapter aims to give some insights on how the tools and the findings presented in this thesis could be used for future research directions. Preliminary results of a study case on catchments with contrasting hydrological behaviour are shown in §6.1. Further development and possible applications of RGM-PRO are listed and briefly commented in §6.2.

6.1 Study case on catchments with contrasting hydrological behaviour and with very accurate input data

One of the main findings of paper III was that the potential added value provided by process maps with high involvement of expert knowledge is severely restricted by large uncertainties in the forcing data and in the measured discharge data. As a consequence, satisfying performances were also reached with simplified mapping approaches, especially for long-lasting events. However, the availability of very accurate precipitation and runoff data would allow their correspondent uncertainties to be neglected. Consequently, as the parameter uncertainty was shown to be unimportant, the remaining predictive uncertainty could be ascribable mainly to the process maps. Furthermore, in paper I, conditions, where the simplified approaches fail in the determination of the DRP, were identified. For example, as topography does not seem to be a good proxy for the storage and infiltration capacity of the soils on the study sites, the simplified mapping approaches often overestimated the runoff intensity on steep sites and underestimated it on flat sites (cp. Figure 3.2 and Table 3.1).

On catchments, where reliable precipitation and runoff data are available, it is very likely that the most complex process maps would outperform the simplified ones. To test this hypothesis, highly accurate process maps derived with the mapping approach of

Schmocker-Fackel (2007), as well as reliable precipitation and runoff data from the PhD Thesis of Schmocker-Fackel (2004) can be used. In the following, preliminary results from the comparison between RGM-PRO and the traditional runoff generation module of PREVAH are shown.

6.1.1 Study area and process maps

The Isert catchment (1.7 km^2) and the Ror catchment (2.1 km^2, Lindist sub-catchment 0.4 km^2) are located closely to each other on the Swiss Plateau in the Canton of Zurich (Figure 6.1). The geological substructure of the catchments consists of Upper Freshwater Molasse, which is covered in most cases by glacial sediments (Hantke, 1967). Both catchments are mostly covered by meadow. Although they look similar in terms of topography, size, and land use, their hydrological reaction to heavy-rainfall is rather different (Figure 6.2). On one hand, the Ror catchment and the Lindist sub-catchment have a strong reaction to rainfall. On the other hand, on the Isert catchment, strongly delayed runoff types dominate and the whole catchment shows therefore a delayed to strongly delayed reaction to rainfall.

6.1.2 Comparison between RGM-PRO and the traditional runoff generation module of PREVAH

A comparison between RGM-PRO and three configurations of the traditional runoff generation module of PREVAH was performed. These configurations include:

- A non-calibrated version of the traditional runoff generation module of PREVAH, from here on referred to as "PREVAH – non cali". A Monte Carlo simulation with 2000 runs was performed for this purpose. The initial parameter ranges are taken from Viviroli et al. (2009b);
- A calibrated version of the traditional runoff generation module of PREVAH, from here on referred to as "PREVAH – cali". The best 10 runs from the Monte Carlo simulation mentioned above were selected for this purpose.
- An upscaling exercise, where the parameter values are calibrated on the smallest catchment and transferred to the larger basin. This configuration is referred to as "PREVAH-Upscaling".

The Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) was used to evaluate the different simulations. Results show that RGM-PRO performed better than the traditional PREVAH (Figure 6.3 and Figure 6.4). In particular, RGM-PRO reproduced the peaks at the beginning of the simulation in a better manner than the traditional PREVAH did. On the Isert catchment, RGM-PRO was able to reproduce the strong delayed hydrological behaviour of the catchment.

An application of the simplified mapping approaches (e.g. Gharari et al., 2011; Müller et al., 2009) on these catchments with contrasting behaviour could furnish further insights into the added value of highly accurate process maps.

Table 6.1 Start and end of the simulated precipitation events. Adapted from Schmocker-Fackel (2004).

Lindist		
Name	Simulation start	Simulation end
Sep01	14.09.2001	23.09.2001
Sep02	20.09.2002	28.09.2002
Oct02	14.10.2002	22.10.2007

Ror und Isert[1]		
Name	Simulation start	Simulation end
May99	12.05.1999	12.05.1999

[1] On Isert, precipitation and runoff data measured by EAWAG

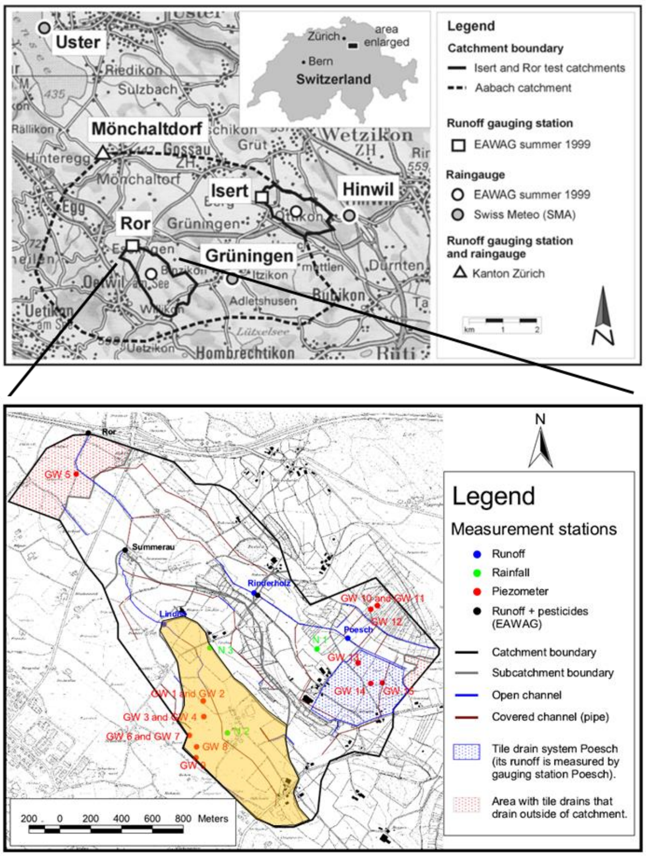


Figure 6.1 Overview of the Isert and Ror catchments, Switzerland. (a) Location of runoff gauging stations and rain gauges. (b) Detail of the Ror catchment, and the Lindist sub-catchment and location of runoff gauging stations and rain gauges. Adapted from Schmocker-Fackel (2004).

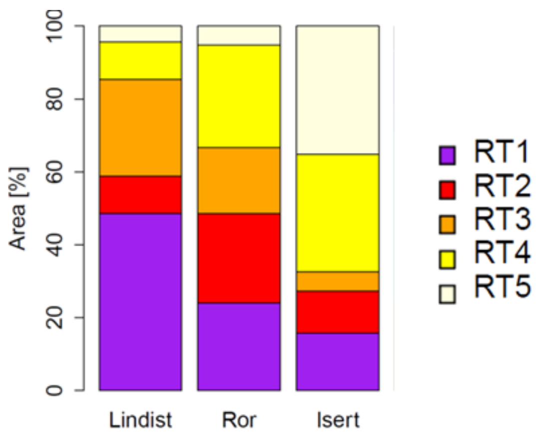


Figure 6.2 Percentage of total catchment area assigned to each runoff type in the Lindist, Ror and Isert catchments with the four different mapping approaches. Adapted from Schmocker-Fackel (2004).

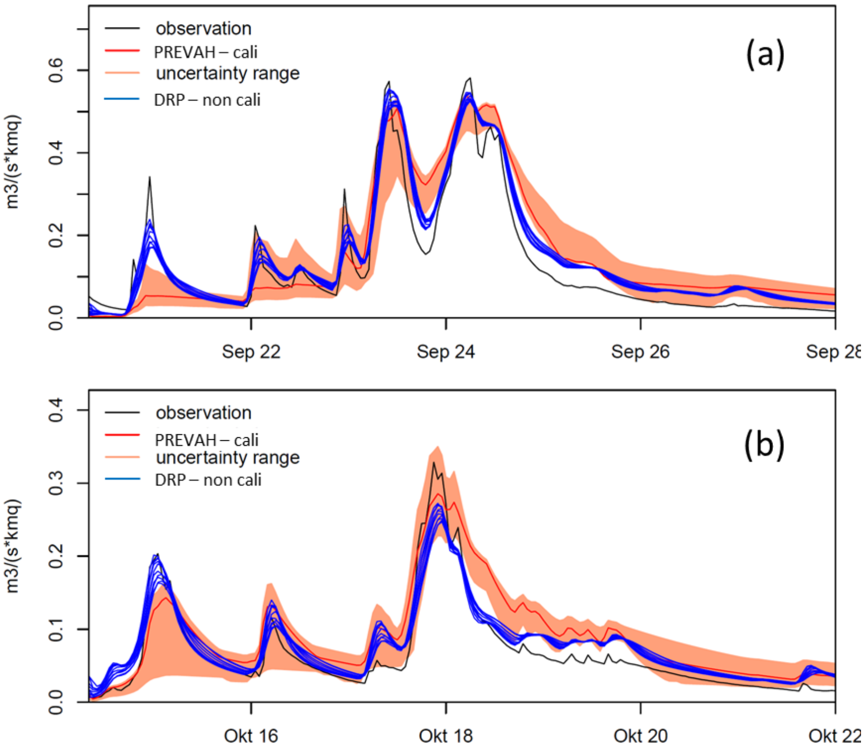


Figure 6.3 Simulated runoff for the Lindist sub-catchment during the rainfall events of September 2002 (a) and October 2012 (b). The black hydrograph corresponds to the measured runoff, whereas the red hydrograph was obtained with the calibrated traditional PREVAH. The uncertainty band refers to the 100 best runs of a Monte Carlo simulation performed with the traditional PREVAH. Finally, the blue hydrographs represent the results of the first 10 runs of a Monte Carlo simulation performed with RGM-PRO.

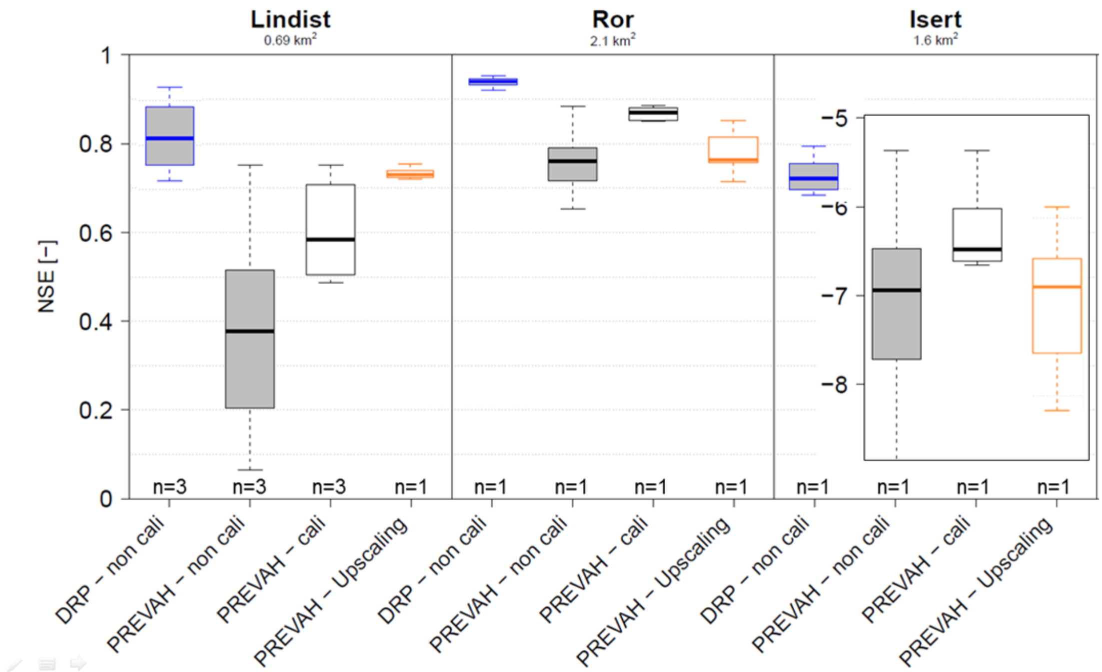


Figure 6.4 Simulation results on the study catchment of Schmocker-Fackel et al. (2004). The grey filling of boxplots indicates the absence of calibration. n corresponds to the number of events represented by each boxplot.

6.2 Further development and applications

Further model development. Several limitations of the studies presented here need to be addressed in future research. First of all, taking into account interception could lead to different results, especially during the beginning of an event. Moreover, a different parameterisation of the runoff concentration could contribute to reduce problems linked with the temporal shift and the excessive smoothness of the simulated hydrographs obtained with RGM-PRO. In fact, the storage time of the linear storage for the concentration of subsurface flow can vary among the different sub-catchments, according to their characteristics (e.g. size, drainage density, etc.). The simulation time step of one hour for investigations on floods is limiting especially when simulating short-duration events (Steinbrich et al., 2016). Sideris et al. (2014) proposed a disaggregation scheme for the generation of precipitation estimates with a resolution of five and ten minutes, but this involves still large uncertainties, and the hourly aggregated data was found to produce higher skill scores in the validation phase. We therefore only included hourly forcing in this study. The equations governing the storage behaviour were solved with an explicit Euler scheme, which has already been found to be responsible for uncertainty in other studies due to the numerical approximations involved (Kavetski and Clark, 2010). To address this issue, an adaptive number of sub-hourly integration steps was introduced according to the intensity of water reaching the upper-zone runoff storage SUZ.

Modelling processes instead of runoff types. The definition of runoff types according to the intensity of contribution to runoff of each DRP has the advantage of taking into account subordinate processes, heterogeneities and the process catena that can occur on a given hillslope (cp. paper II). However, this goes at the expense of an accurate distinction between overland and subsurface flow for those runoff types, where different runoff mechanism can occur (e.g. RT4, where SOF3 and SSF3 can take place). Conversely, dealing with DRPs instead of RTs would allow the drainage processes to be better represented within the model. However, given that the number of DRP classes is greater than that of runoff types (e.g. nine DRPs vs. five RTs according to Scherrer AG, 2006), the number of parameters to allocate a priori, and, consequently, the overfitting risk would increase. In literature, some studies dealing exclusively with DRPs already exist (e.g. Haag et al., 2016; Hellebrand et al., 2011), whereas others make use of DRPs for the runoff generation, and RTs for the runoff concentration (e.g. Casper et al., 2015; Gronz, 2013).

RGM-PRO output as input for other studies. A more realistic spatial representation of the runoff distribution within a given catchment entails the potential for improving studies which use the results from hydrological models as input data for further simulations. This is the case for studies on land slides, debris flows, large wood in torrents and rivers etc. Also, studies on transport of agrochemicals could benefit from a spatially differentiated representation of runoff. In this case, however, an explicit consideration of the flow paths within the model should be preferred over a sub-grid parameterisation of the DRPs like the one developed for RGM-PRO.

DRP concept for droughts. The process-based modelling chain used in this dissertation could also be applied to simulate low flows, provided that some adjustments are undertaken. Concerning the process maps, the DRPs should be mapped with an explicit focus on droughts, as other catchment characteristics like the storage capacities and drainage potential of soils become of crucial importance (e.g. Floriancic, 2014). With regard to the model setup, an event-based model like RGM-PRO is not yet suitable for drought simulations, as the evapotranspiration process, which plays an important role, should be explicitly represented within the model. Some studies tried already to address this issue. For example, Rogger et al. (2012) defined so-called “surface runoff response units“ for fast processes above ground, and so-called “hydro-geological response units” to discern between runoff in shallow or deep groundwater. The latter were derived based on orthophotos, geological maps, hydro-geological maps, DTM, maps of unconsolidated sediments and field observations. Also, Casper et al. (2015) adapted the water balance model LARSIM to deal with both high and low flows.

DRPs and snow. To extend the applicability of RGM-PRO to snow-related events, and to investigate the influence of the presence of snow on runoff generation mechanisms, the findings of this PhD project could be linked with those of a parallel project on rain on snow events (Würzer et al., 2016, 2017).

Acknowledgements

Three years ago, during a summer school in Luxemburg, I made a promise to two PhD candidates I met there: "If I will ever manage to finish my PhD, I will bungee jump from the Verzasca dam!" Well, we will see if the following lines are to be understood as acknowledgements rather than as testament…

The amount of people I would like to thank is *tremendous*. Massimiliano Zappa deserves certainly to be mentioned as first. Expert (definitely more dry than wet) hydrologist, great boss, fine music and dessert *connoisseur*. Thank you for believing in me. I would also like to express my gratitude to Jan Seibert for accepting the supervision of my PhD thesis, to Marco Borga for acting as external examiner, and to the other members of my PhD committee: Ross Purves, and Katharina Liechti. Many thanks to the project partners, the wet hydrologists Simon Scherrer, Peter Kienzler, and Michael Margreth for sharing their expertise and for providing valuable feedback throughout the project.

I thank the Federal Office for the Environment and in particular Petra Schmocker-Fackel for funding my PhD position and WSL for having extended it for the time necessary. Thanks to the Graduate School of the Department of Geography and to the Swiss Hydrological and Limnological Society for providing travel grants. I would also like to thank Manfred Stähli and the entire research unit of Mountain Torrents and Mass Movements for the pleasing working environment, in which I completed my PhD thesis. Thanks also to H2K for letting me feel part of your group.

Special thanks to the hackers behind the malware I managed to download and install on my computer in July 2016. I lost a good 30 GB of data including the drafts of paper II, which of course weren't saved anywhere else. At least, they gave me the highest motivation to recover in few days what I wrote in few weeks. Thanks Rahel and Christoph for having decided to write your master thesis within my PhD project. Thanks to Alex, Alexandre, Andrea, Anil, Käthi, Nicolas, Norina, and Matthias for the proofreading of this thesis. Thanks to Lara Gut for everything!

A very Italian *grazie mille* to the special people I met during my Swiss experience. Thanks Anil for having become my new Fronza <3; thank you Alice for marrying my new Fronza. Thanks Matthias for introducing me to S. Bestiale; thanks Saskia for sharing the hottest office at WSL with me; thanks Nicolas for letting me win all the ping pong matches. Really, all of them. Thanks Thomas for offering us the cheapest flat in Zurich. Thanks Michi for bringing luck during football matches. Why didn't we watch the final of Champions League together? Thanks Sandro for being forte eeeh.. sei forte! Thanks to Mr. Eberli for his high commitment in repairing my beloved *töff*. Thanks Luca for reminding me that not only the *Puschtra Wölfe* lose all the times, there is also Ambrì Piotta.. Thanks Sia for having acknowledged me in your PhD thesis ☺

Many, many thanks to my family in Italy for the never-ending support they provide me and for the systematic legal (?) import of every kind of food specialty from Italy during my stay in Switzerland. Finally, the biggest THANK YOU goes to my family in Switzerland. Thanks Pippetta for being the most important gender-free cat of my life, and thank you Valeria for your love, patience, and support through these years. *Spero che crepi!*

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I. Mapping dominant runoff processes: an evaluation of different approaches using similarity measures and synthetic runoff simulations

Hydrology and Earth System Sciences, DOI:10.5194/hess-20-2929-2016.

Manuel Antonetti[a,b], Rahel Buss[a], Simon Scherrer[c], Michael Margreth[d], and Massimiliano Zappa[a]

Abstract

The identification of landscapes with similar hydrological behaviour is useful for runoff and flood predictions in small ungauged catchments. An established method for landscape classification is based on the concept of dominant runoff process (DRP). The various DRP-mapping approaches differ with respect to the time and data required for mapping. Manual approaches based on expert knowledge are reliable but time-consuming, whereas automatic GIS-based approaches are easier to implement but rely on simplifications which restrict their application range. To what extent these simplifications are applicable in other catchments is un- clear. More information is also needed on how the

different complexities of automatic DRP-mapping approaches affect hydrological simulations.

In this paper, three automatic approaches were used to map two catchments on the Swiss Plateau. The resulting maps were compared to reference maps obtained with manual mapping. Measures of agreement and association, a class comparison, and a deviation map were derived. The automatically derived DRP maps were used in synthetic runoff simulations with an adapted version of the PREVAH hydrological model, and simulation results compared with those from simulations using the reference maps.

The DRP maps derived with the automatic approach with highest complexity and data requirement were the most similar to the reference maps, while those derived with simplified approaches without original soil information differed significantly in terms of both extent and distribution of the DRPs. The runoff simulations derived from the simpler DRP maps were more uncertain due to inaccuracies in the input data and their coarse resolution, but problems were also linked with the use of topography as a proxy for the storage capacity of soils.

The perception of the intensity of the DRP classes also seems to vary among the different authors, and a standardised definition of DRPs is still lacking. Furthermore, we argue not to use expert knowledge for only model building and constraining, but also in the phase of landscape classification.

[a] Swiss Federal Research Institute WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland.

[b] Department of Geography, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland.

[c] Scherrer AG, Schönmattstrasse 8, 4153 Reinach, Switzerland.

[d] SoilCom GmbH, Probusweg 22, 8057 Zurich, Switzerland.

1. Introduction

Conceptual rainfall–runoff models perform well on gauged basins but appear to be limited in reproducing the hydrological behaviour of ungauged catchments (Hrachowitz et al., 2013). Expert knowledge about the different runoff processes that can occur on a catchment can improve the hydrological simulations for such ungauged basins. For example, it can be used to design process-tailored model structures aiming to be right for the right reason (Klemeš, 1986). Furthermore, it can help to reduce the need for calibration by constraining the parameter values or modelled output to guarantee consistency with the reality (Franks et al., 1998; Gharari et al., 2014; Hrachowitz et al., 2014; Seibert and McDonnell, 2002). Hydrological classifications based on landscapes with similar hydrological behaviour can be useful regionalisation tools for predictions in ungauged basins. In this case, once a model structure and its parameters have been identified for each landscape in a gauged catchment, they are transferred to an ungauged catchment where the landscapes have similar hydrological behaviour (e.g. Beran, 1990; Mosley, 1981; Viviroli et al., 2009b).

In recent decades, several methods have been developed to quantify the spatial extent and to identify the distribution of areas where a specific runoff process occurs. The topographic wetness index (Beven and Kirkby, 1979), as an example of index-based methods, allows areas prone to saturation over- land flow (SOF) to be identified using only topographical in- formation. Similarly, Woods et al. (1997) developed a topographic index for areas where subsurface flow (SSF) occurs. Another well-established methodology involves the explicit definition of hydrological response units (HRUs), which can be identified according to geological, ecological, pedological, and/or topographical criteria (e.g. Flügel, 1995; Ross et al., 1979). For example, Markart et al. (2011) developed a method for assessing surface runoff coefficients and surface roughness in the case of extreme precipitation events. Similarly, Dobmann (2010) introduced a way to map runoff disposition, defined as “the tendency of water to become displaced downstream due to gravity in such a way as to cause damage” (Kienholz et al., 1998).

Although these methods represent an important basis for the determination of runoff peaks and return periods of flood events, they cannot reproduce the full range of runoff responses that can be observed on a site. To improve the HRU approach, several hydrological classifications have been developed based on the concept of dominant runoff process (DRP), i.e. the runoff generation mechanism that contributes most to runoff (Blöschl, 2001).

DRP classifications may be manual or automatic (Table I.1). Manual approaches are based on extensive field investigations, and the interpretation and the upscaling of the results on expert knowledge (e.g. Scherrer and Naef, 2003). In contrast, automatic methods generally rely on GIS and on algorithms based on simplifications of expert knowledge (e.g. Peschke et al., 1999).

Table I.1 List of hydrological classifications based on DRPs, the data they require, and the number of output classes (A: automatic; M: manual).

	Approach	**Topography**	**Land use**	**Geology**	**Soil maps**	**Drainage maps**	**Forest-vegetation**	**Extensive field investigations**	**Number of output classes**
Boorman et al. (1995)	A				X				29
Peschke et al. (1999)	A	X	X	X	X				7
Tilch et al. (2002)	M	X		X					6
Waldenmeier (2003)	A	X					X		7
Scherrer and Naef (2003)	M	X	X	X	X	X	X	X	9
Schmocker-Fackel et al. (2007)	A	X	X	X	X	X	X	X	12
Tetzlaff et al. (2007)	A	X	X	X				X	5
Müller et al. (2009)	A	X	X	X					9
Gharari et al. (2011)	A	X							3
Hümann and Müller (2013)	A	X	X	X					10
Gao et al. (2014)	A	X							4

Automatic approaches differ in which data they require. Some rely on topographical information only (e.g. Gharari et al., 2011), while others use all the available information for an area (e.g. Schmocker-Fackel et al., 2007). The data requirement is closely linked to the time it takes to map the DRPs, ranging from a few hours with simple data input to months if the data are derived from extensive field investigations (e.g. Tezlaff et al., 2007).

The output classes of the classifications also differ. All methods distinguish at least between infiltration excess (Hortonian) overland flow (HOF) and SOF, and between SSF and deep percolation (DP) (e.g. Gharari et al., 2011; Gao et al., 2014). Several approaches also provide information on the intensity of the SOF and SSF processes, where the numbers from 1 to 3 represent the delay in their reaction to rainfall, with 1 representing an almost immediate reaction, 2 a slightly delayed one and 3 a strong delayed one (e.g. Scherrer and Naef, 2003; Schmocker-Fackel et al., 2007; Müller et al., 2009; Hümann and Müller, 2013). Boorman et al. (1995), however, classified expected hydrological behaviour according to 29 classes in the Hydrology Of Soil Types classification of Great Britain.

Several algorithms have been developed exclusively for specific catchments, and are therefore not suitable for regionalisation purposes. For instance, Tilch et al.'s (2002) classification is based on the genesis of the hillslope and its covering material. Similarly, Waldenmeyer (2003) determined DRPs from a forestry site map, and Gao et al. (2014) linked the presence of forest to the hillslope exposition in the barely inhabited Upper Heihe catchment in China. These simplifications limit the applicability of the methods to other catchments.

All these methods aim to map the spatial distribution of DRPs in a realistic way, but only few have investigated the transferability of the algorithms to other catchments. Furthermore, it remains unclear how the different time and data requirements of the mapping approaches affect hydrological simulations. The objective of this paper is therefore to (i) test the suitability of different automatic DRP-mapping approaches for mapping ungauged catchments, and (ii) quantify the uncertainty of hydrological simulations due to different spatial representations of DRPs.

DRP-maps were produced for two catchments on the Swiss Plateau using the automatic approaches of Schmocker-Fackel et al. (2007), Müller et al. (2009) and Gharari et al. (2011). These were then compared with reference maps produced using manual mapping according to Scherrer and Naef (2003). To assess how similar the automatically derived DRP-maps are to the reference maps, a measurement of agreement, Fuzzy Kappa (Hagen-Zanker, 2009), a measurement of association, Mapcurves (Hargrove et al., 2006), and a class comparison were carried out. Furthermore, the effects of the differences between the DRP-maps on synthetic runoff simulations were investigated with an adapted version of the well-established PREVAH model (Viviroli et al., 2009b).

2. Study sites

Our analyses are performed on two small catchments on the Swiss Plateau. The Dorfbach Meilen is a creek which drains a 4.6 km^2 catchment and flows into Lake Zurich (Figure I.1). The elevation of the catchment ranges from 409 to 850 m a.s.l.. It is mainly covered by grassland (49.4%) and forest (39%) and, to a lesser extent, arable land (3.6%) and settlements (8%). The basin is characterised by Upper Freshwater Molasse with conglomerate in the shallow subsurface (Hantke et al., 1967). A large part of the catchment is covered by brown earth soils with normal permeability and storage capability. Soils with less permeable soils and wetlands are less widespread but play an important role in runoff generation.

The Reppisch catchment up to Birmensdorf is situated in the southwest of Canton Zurich, Switzerland (Figure I.2). It has an area of 22 km^2, of which 48 % is covered by forest, 42 % by grassland, and 7 % by settlements. The elevation of the catchment ranges from 467 to 894 m a.s.l.. The geological substructure of the catchment forms the Upper Freshwater Molasse, composed of sandstone and marl, and is covered in most cases by glacial sediments (Hantke et al., 1967; Pavoni et al., 1992; Bolliger et al., 1999). Gravel deposits can be found along the Reppisch river, while a number of smaller alluvial fans were accumulated by its many tributaries. Brown earth soils with normal permeability and storage capability cover most of the catchment, while soils with low permeability are less widespread.

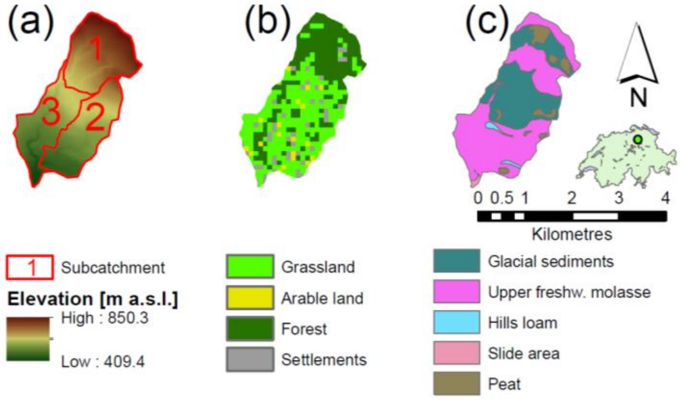

Figure I.1 Overview of the Meilen catchment, Switzerland. (a) Digital terrain model (25m resolution) subdivided into three subcatchments; (b) land-use map (100m resolution); (c) geology map (data: BFS GEOSTAT/Federal Office of Topography swisstopo).

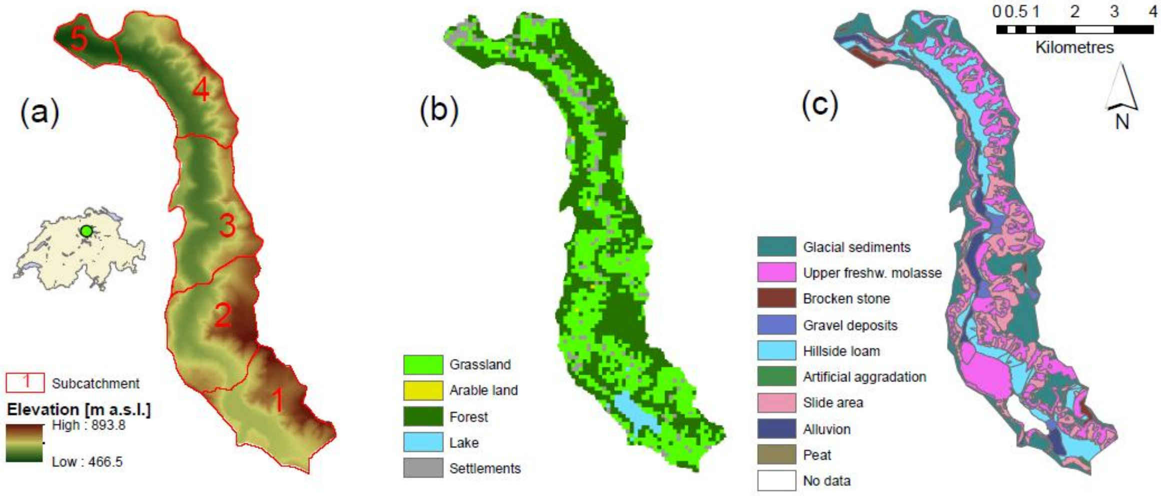

Figure I.2 Overview of the Reppisch catchment, Switzerland. (a) Digital terrain model (25m resolution) subdivided into five sub-catchments; (b) land-use map (100m resolution); (c) geology map (data: BFS GEOSTAT/Federal Office of Topography swisstopo).

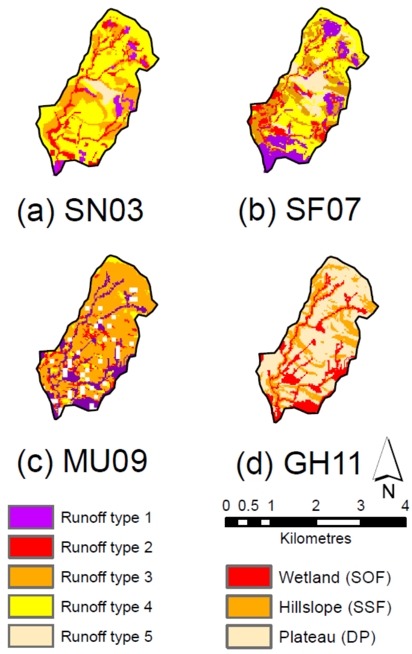

Figure I.3 DRP maps for the Meilen catchment: (a) reference map according to Scherrer and Naef (2003) and automatically derived map according to (b) Schmocker-Fackel et al. (2007), (c) Müller et al. (2009), and (d) Gharari et al. (2011).

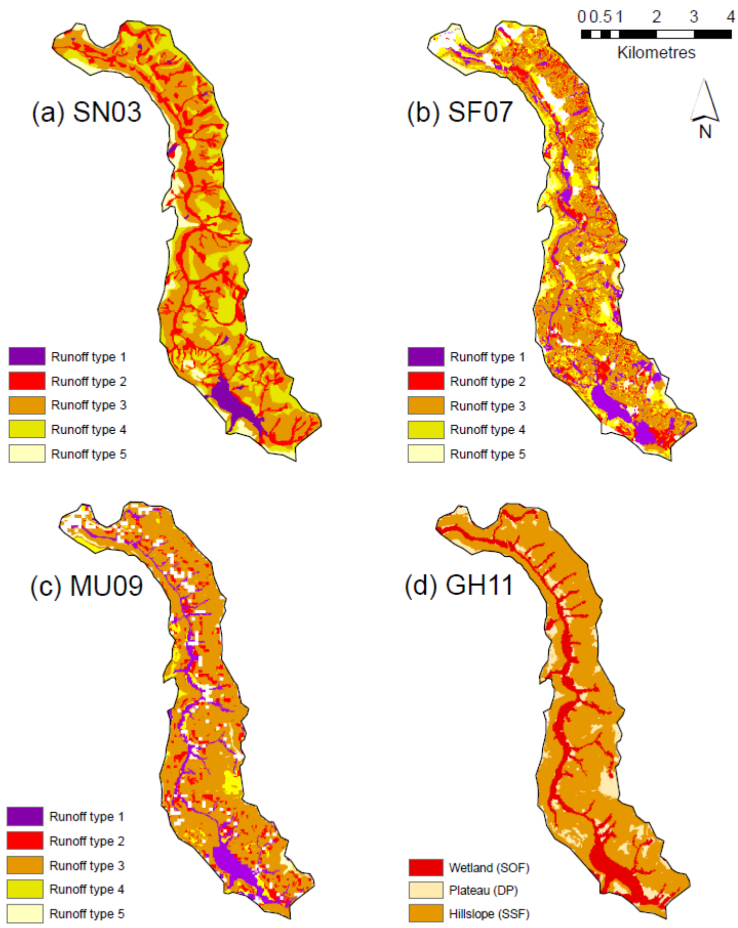

Figure I.4 DRP maps for the Reppisch catchment: (a) reference map according to Scherrer and Naef (2003) and automatically derived map according to (b) Schmocker-Fackel et al. (2007), (c) Müller et al. (2009), and (d) Gharari et al. (2011).

Table I.2 Reclassification of DRPs according to RTs (HOF = Hortonian Overland Flow; SOF = Saturation Overland Flow; SSF = Subsurface Flow; DP = Deep percolation; 1 represents an almost immediate reaction, 2 a slightly delayed one and 3 a strong delayed one). Adapted from Naef et al. (2000).

Runoff type (RT)	DRP	Runoff intensity
1	HOF1/2, SOF1	Fast
2	SOF2, SSF1	Slightly delayed
3	SSF2	Delayed
4	SOF3, SSF3	Strongly delayed
5	DP	Not contributing

3. Data and methods

3.1 DRP-mapping approaches

Manually derived DRP-maps based on the decision scheme of Scherrer and Naef (2003), referred to here as SN03-maps, are available as shape-files for both study sites and were used as reference maps (Figure I.3a and Figure I.4a). These DRP-maps are developed in different steps as follows: 1) Information about the land-use, vegetation, soil, geology, hydrogeology and topography of the catchment are collected. 2) Based on these data, the DRPs are initially estimated using expert knowledge, and locations where estimations are not straightforward are identified. 3) On these sites, soil profiles are investigated and the DRP at the plot-sites identified according to the decision schemes for long-lasting events (i.e. with precipitation intensity less than ca. 20 mm/h) of Scherrer (2006). 4) After the analysis of the field investigations, the DRPs can be determined for the hillslopes and finally for the whole catchment. 5) The DRPs are reclassified into five different runoff types (RTs) with respect to the runoff intensity (Table I.2).

Schmocker-Fackel et al. (2006) developed a strategy to simplify the decision schemes of Scherrer and Naef (2003) and determine the DRPs automatically within a GIS environment. Basically, the method relies on a soil map with high resolution (1:5000) of Canton Zurich and information about the soil water regime, soil depth, and the soil's physical and chemical properties. Where information on soil is lacking, an expert-based soil prediction model was used to derive DRPs from information about forest communities, the slope and shape of hillslopes, the surface water network and the geology (Margreth et al., 2010). This step is relatively time-consuming, since the soil prediction model has to be adapted to each catchment according to the information available. Therefore, several days of fieldwork are necessary. The DRP-maps derived with this approach for this study are available as shape-files, referred to hereafter as SF07-maps (Figure I.3b and Figure I.4b).

Table I.3 Dependency of the DRP on the slope and permeability of the substratum for grassland, arable land and forest, according to Müller et al. (2009).

Slope	Impermeable substratum		Permeable substratum
[%]	Grass- and arable land	Forest	Grass-, arable land and forest
0 – 3	SOF3	SOF3	DP
3 –5	SOF2	SSF3	DP
5 – 20	SSF2	SSF2	DP
20 – 40	SSF1	SSF2	DP
> 40	SSF1	SSF1	DP

Müller et al. (2009) proposed a further simplification of the Schmocker-Fackel et al.'s (2007) approach based on GIS and valid for prolonged rainfall events. The method combines information on the permeability of the geological substratum, land-use and slope, but excludes soil information. It results in the same DRP classes as those proposed by Scherrer and Naef (2003), and involves: first, using a DTM analysis to identify classes of slopes; then, classifying the geological substrata of the catchments as either permeable or impermeable; and finally, combining the pre-processed digital data to obtain the DRP (Table I.3). Hümann and Müller (2013) extended the approach proposed by Müller et al. (2009) to forested areas and to different event types. Since the reference maps refer to long-lasting events, the Müller et al.'s (2009) approach was used for this study.

DRP-maps based on Müller et al. (2009), referred to here as MU09 (Figure I.3c and Figure I.4c), were derived for the two study sites with a spatial resolution of 25 m based on following assumptions: (i) Riparian zones, i.e. the spots around the river network, were classified as SOF1. The extension of these areas were defined by taking into consideration the cells with a Height Above the Nearest Drainage (HAND), i.e. the height of a DTM-cell less the elevation of the river network where the cell drains (Rennó et al., 2008), that is lower than 1.2 m. (ii) Settlement areas were not considered in the current study as the resolution of the land-use map used (100 m) was not high enough to obtain a realistic representation of their spatial distribution.

As a further simplification, topography-based classifications were developed with the assumption that the topography can be seen as a proxy for the geology, soil, land-use, climate and, consequently, DRPs (Savenije, 2010). In addition to traditional topographical descriptors (e.g. elevation, slope and exposition), these methods are based on the HAND value, which represents, in turn, a rearrangement of the "elevation-above-stream" proposed by Seibert and McGlynn (2006). HAND-based classifications have been used to define classes of soil water environments, where a single runoff generation mechanism dominates (Nobre et al., 2011; Gao et al., 2014). Gharari et al. (2011) found that the combination between HAND and slope provided the most suitable descriptors for a topography-based classification of DRPs. The mapping approach distinguishes between three landscape classes. Areas below a certain HAND threshold value are called "wetland" (subject to SOF). The remaining regions are further divided into two classes: "hillslope", subject to SSF, and "plateau", subject to DP, depending on whether the slope is above or below a certain threshold value. Since these threshold values are not unconditionally transferable to other catchments, a sensitivity analysis was carried out on both study sites. Different combinations of threshold values were tested, and the resulting maps were compared with SN03 at a spatial resolution of 25 m. We selected the maps with the best Mapcurve-score (cf. 3.2) for this study, and refer to them as GH11 (Figure I.3d and Figure I.4d). The threshold values obtained are in agreement with those of Gharari et al. (2011) in a central European catchment (Figure S1).

3.2 Map comparison

To test the suitability of different approaches for automatically mapping the DRPs on ungauged catchments, a class comparison between automatically derived DRP-maps and the reference maps was carried out for the two study sites. The percentage of total catchment area assigned to each RT, and the percentage of discrepancy between the RTs in the automatic DRP-maps and those in the reference maps were calculated. To deal with the difference in number of classes between the GH11-maps and reference maps, an expedient step was introduced. Since none of the three classes of GH11-maps (wetland, hillslope and plateau) is necessarily comparable to a specific class of the reference maps, the 5 RTs of the SN03-maps were reclassified into 3 classes covering every possible combination (Table S1), resulting in 6 new reference maps. These were compared one by one with the GH11-maps. In addition, the discrepancies between the MU09-maps and the reference maps were highlighted in a deviation map to identify the spots where the difference in the RTs is greater than 2 and to help identify the possible causes of incorrect mapping.

To account for fuzziness in the definition of the RTs, a measure of agreement, fuzzy kappa (K_{Fuzzy}), was used. The method was proposed by Hagen-Zanker (2009) to extend the well-established Cohen's Kappa (Cohen, 1960), and to take into account the fuzziness of categories, allowing some pairs of classes to be more similar than others, as well as the fuzziness of location, given that cells tend to be at least slightly spatially correlated. To take the fuzziness of categories into account, a similarity matrix was defined, where each pair of classes was assigned a number between 0 (totally distinct) and 1 (completely identical). The extent to which neighbouring cells influence the cell in question is defined by a distance decay function. An overall measure of similarity between two maps can be obtained by using the following equation:

$$K_{Fuzzy} = \frac{P-E}{1-E} \ [-] \qquad \text{Eq. 1}$$

where P represents the mean agreement of the two compared maps, weighted by the expected agreement E. K_{Fuzzy} ranges from 0 (fully distinct maps) to 1 (fully identical maps). For this study, the fuzzy kappa algorithm implemented in the software Map Comparison Kit 3 (Visser and de Nijs, 2006) was used. We assumed that contiguous RTs are similar to some extent and the corresponding degree of similarity was set to 0.25. An exponential decay function with a halving distance of one cell is adopted.

Given that the number of classes in the GH11-map is different from that in the reference maps, the goodness-of-fit (GOF) measure called Mapcurves (Hargrove et al., 2006) was used to quantify the degree of spatial concordance between the automatic DRP-maps and the reference maps. For each of the existing classes in two maps, a GOF-score [unit-less] was calculated according to the following equation:

$$GOF_X = \sum_{Y=1}^{n} \left(\frac{C}{A} \cdot \frac{C}{B} \right) \qquad \text{Eq. 2}$$

where A is the total area [m^2] of a given class X on the map being compared, B is the total area [m^2] of a class Y on the reference map, C is the intersecting area [m^2] between X and Y when the maps are overlaid, and n is the total number of classes on the reference map. The sum of this product gives a GOF-value for a particular class. The overall Mapcurves (MC)-score is given by the area under the curve obtained by plotting the GOF-scores on the abscissa and the percentage of map classes with a GOF-score larger than a particular value on the ordinate. An MC-score of 1 represents a perfect fit, while an MC-score of 0 means that there is no spatial overlap between the classes of two maps. Both the shape of the Mapcurves and the MC-score differ when the compared map is used as a reference map. This is because the MC-score depends on the average size and number of the patches in each class of the maps being compared. Hargrove et al. (2006) argue that the combination of compared map and reference map that has the highest MC-score must be chosen. However, by doing so, the coarser maps would be advantaged. Therefore, for this study, SN03-maps were always set as reference maps. A detailed description of the two similarity measures is reported in Hagen-Zanker (2009) and Hangrove et al. (2006), while applications in hydrology are described in Speich et al. (2015) and Jörg-Hess et al. (2015).

To identify those landscapes where automatic approaches perform better, the comparison measures were applied to the single sub-catchments, at a high spatial resolution, to take into account the added value of the finest maps. For this reason, the shapefiles were rasterised and the coarser maps were resampled to a grid resolution of 2 m.

3.3 Synthetic runoff simulations

To assess how the differences between the automatic DRP-maps affect a hydrograph, synthetic runoff simulations were carried out. This approach was inspired by Weiler and McDonnell (2004), who suggested using numerical experiments to isolate hypotheses and investigate their influence on the model output. In a recent review paper, Fatichi et al. (2016) acknowledge this studies to be different from those aiming at comparing performances of different models or validating model results. The word “synthetic” implies therefore that the focus is exclusively on how the different DRP-maps influence the simulated runoff, and not on how well the model reproduces a measured discharge. The model used for this study is an adapted version of the runoff generation module of the PREVAH model (Viviroli et al., 2009a). It is distributed (500 m grid resolution) to take into account the spatial variability of the input data, which consists of a combination of radar and traditionally measured rainfall data (Sideris et al., 2014). For each cell, the percentage of each RT is taken into account to avoid losing information because of the grid resolution.

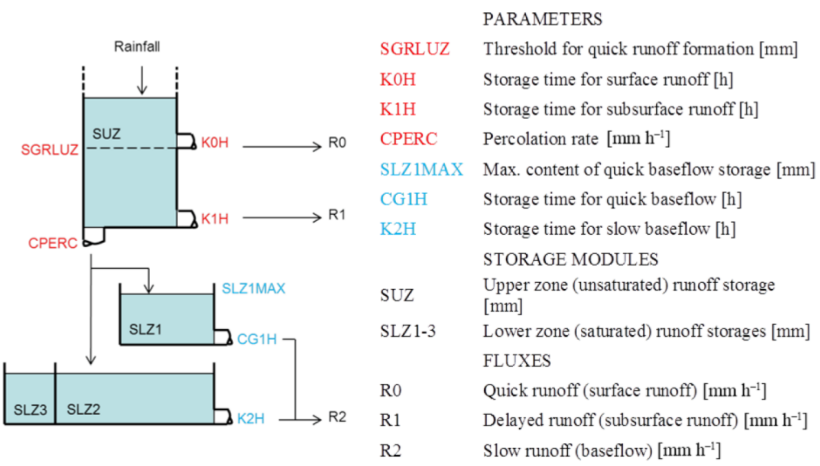

Figure I.5 Runoff generation module of PREVAH, adapted from Viviroli et al. (2009b). Parameters in blue are averaged for the whole catchment, while parameters in red are adapted stepwise to the RTs.

The model does not take interception, evapotranspiration and soil moisture into consideration (Figure I.5). The rainfall directly recharges the upper zone (unsaturated) runoff storage (SUZ), where the storage times for the surface runoff (K0H) and subsurface runoff (K1H) regulate the generation of the runoff. The threshold for quick runoff formation (SGRLUZ) determines the separation between surface runoff (R0) and subsurface runoff (R1). A maximum percolation rate (CPERC) controls the percolation to the groundwater storage, which is divided into a quick-leaking storage (SLZ1) and two slow-leaking storages (SLZ2 and SLZ3; Schwarze et al., 1999). The storage capacity of SLZ1 is limited by a maximal storage charge (SLZ1MAX), while its contribution to the slow runoff (R2) is regulated by the storage time for quick baseflow (CG1H). SLZ2, which only receives the fraction of percolation not absorbed by SLZ1, is controlled by the storage time for slow baseflow (K2H). With this model configuration, it is possible to detect the effects of differences between the different maps in terms of both extent and distribution of RTs. The difference in extent of RTs gives more weight to one or other of the parameter sets. If the RT extent is the same, the location of the RTs on the catchment plays a role since the rainfall input can vary from cell to cell.

We assume that the properties of the different RTs can be represented by varying the parameter values of the model employed. For example, the tendency for RT1 and RT2 to generate overland flow was represented by assigning low values of SGRLUZ and CPERC. Furthermore, the K0H values assigned to RT1 and RT2 were set as low since the fast contributing areas were assumed to be close to the river network. On areas where either HOF or DP dominates, the subsurface flow was neglected and K1H was set to higher values (e.g. 1000 h). As the baseflow generation does not necessarily depend on the RTs, the parameters of the SLZ1, SLZ2 and SLZ3 were defined a priori as averaged values for both catchments and kept constant for the simulations. The values selected were based on the results of Viviroli et al. (2009a), who identified a range of suitable values for each parameter of PREVAH for flood estimation in ungauged mesoscale catchments in Switzerland.

To investigate the sensitivity of the model output with respect to the definition of parameter values based on the RTs, the parameters were defined in a stepwise process, resulting in 16 different parameter combinations (Table S2). First, the 5 RTs were assigned the same set of parameter values and no information about the RTs was thus included. In the second step, the value of each parameter controlling the SUZ was defined with respect to the RT one at the time, and the value of the other parameters was left unchanged. The same procedure was then repeated by defining the values based on the RTs of two, three and finally all the parameters at the same time. As in the class comparison (see section 3.2), an expedient step was introduced to take into account the fact that there were fewer classes of GH11-maps. Every possible combination of the five predefined values for each parameter was covered, provided that the parameters fulfilled the following condition:

$$\vartheta_{WETLAND} \leq \vartheta_{HILLSLOPE} \leq \vartheta_{PLATEAU} \qquad \vartheta = SGRLUZ, K0H, K1H, CPERC \qquad \text{Eq. 3}$$

This resulted in 10 different runs for each parameter combination (Table S3), with one exception: the storage time for the subsurface flow K1H. This was set at 1000 h for wetland (SOF) and plateau (DP), since no subsurface flow was expected there.

Synthetic simulations were carried out on the two study sites over the time period which ranges from 16/06/2014 to 15/08/2014. A modified version of the Nash-Sutcliffe Efficiency (NSE; Nash and Sutcliffe, 1970), in which the observed runoff is replaced by the runoff simulated with the reference maps, was therefore used as objective function (Eq. 4).

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_{SN03,i} - Q_{DRP,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{SN03,i} - \overline{Q_{SN03}}\right)^2} \; [-] \qquad DRP = SF07, MU09, GH11 \qquad \text{Eq. 4}$$

4. Results

According to the reference (SN03) maps, the two study sites differ slightly in their RT distributions (Figure I.6). In the Reppisch catchment, areas with a delayed runoff contribution (RT3) prevail (45% of the catchment area), while, in the Meilen catchment, areas with strongly delayed runoff contribution (RT4) cover 55.3% of the catchment. SF07-maps reproduce the RT distribution fairly, although they slightly overestimate the fast contributing areas (RT1), and underestimate the areas with strongly delayed contribution (RT4) in the Meilen catchment. The RT distribution of the MU09-maps deviate from the one of the reference maps. They considerably overestimate the delayed contributing areas (RT3) and, to a lesser extent, the fast ones (RT1), at the expense of the remaining RTs. The runoff contribution is consistently overestimated especially in the Meilen catchment, whereas in 64% of the whole catchment the RT is faster compared with the SN03-map (Figure I.7).

The distribution of landscape classes of GH11-maps in the Meilen catchment (Figure I.6b) agrees well with the reference map, if the landscape class “hillslope” is assumed to correspond to RT3, “wetland” to the union of RT1 and RT2, and “plateau” to both RT4 and RT5. However, this consideration no longer holds true in the Reppisch catchment, where the percentage of the total catchment mapped as “hillslope” (68%) markedly exceeds the one mapped as RT3 in the reference map (45%). Considering each possible reclassification into 3 classes of the 5 RTs of the SN03-maps (Table S1), the GH11-maps, on average, estimate the runoff contribution as lower than the SN03-maps estimate (Figure I.7).

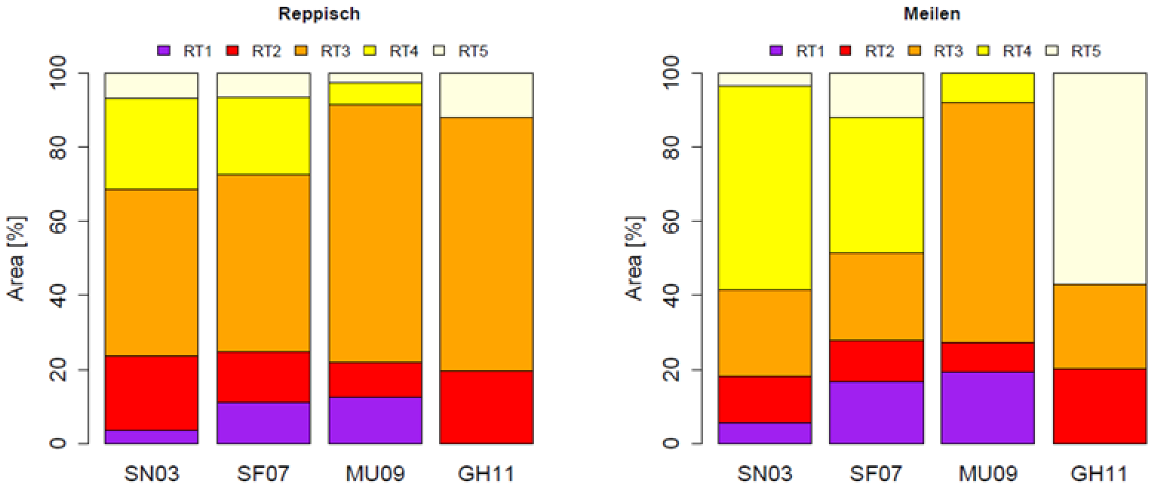

Figure I.6 Percentage of total catchment area assigned to each runoff type in the Reppisch and Meilen catchments with the four different mapping approaches.

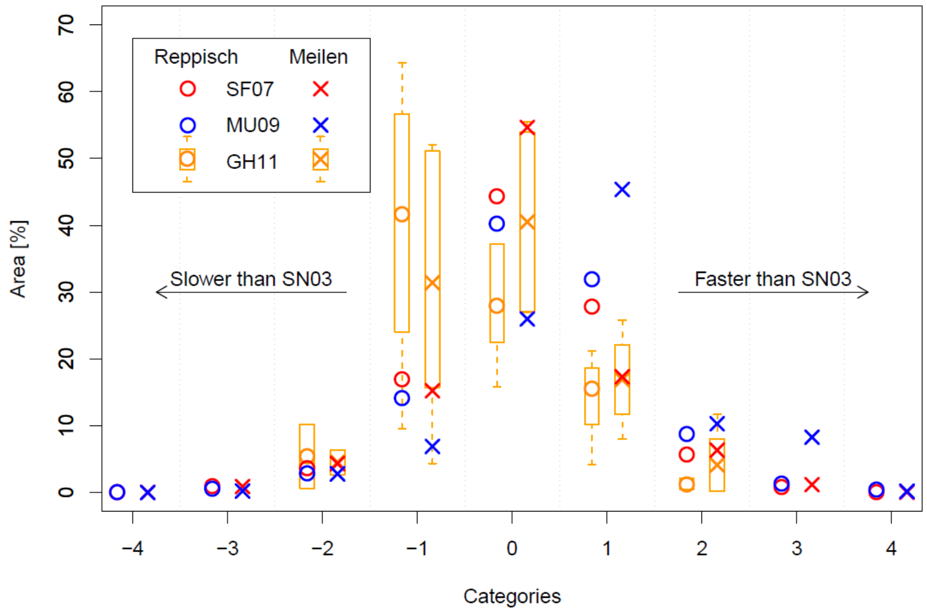

Figure I.7 Distribution of the class deviations of the different automatic mapping approaches from the reference maps (circles refer to the Reppisch catchment and crosses to the Meilen catchment). The boxplots show median and interquartile ranges from the comparison between GH11 maps and the reclassified reference maps.

Table I.4 List of areas identified in Fig. 8 with the automatically and manually derived DRPs (RTs), and a possible explanation for their deviation.

Area	DRP (RT) on MU09 map	DRP (RT) on SN03 map	Explanation
1	SSF2 (RT3)	DP (RT5)	Moraine not necessarily impermeable
2	SSF1 (RT2)	SSF3 (RT4)	Although high slope, high storage capacity of soil
3	DP (RT5)	SSF2 (RT3)	Alluvium not necessarily permeable
4	SOF3 (RT4)	SOF2 (RT2)	Although low slope, low storage capacity of soil
5	SOF1 (RT1)	SSF2 (RT3)	Coarse resolution of DTM
6	SOF1 (RT1)	SSF2 (RT3)	Coarse resolution of land-use map

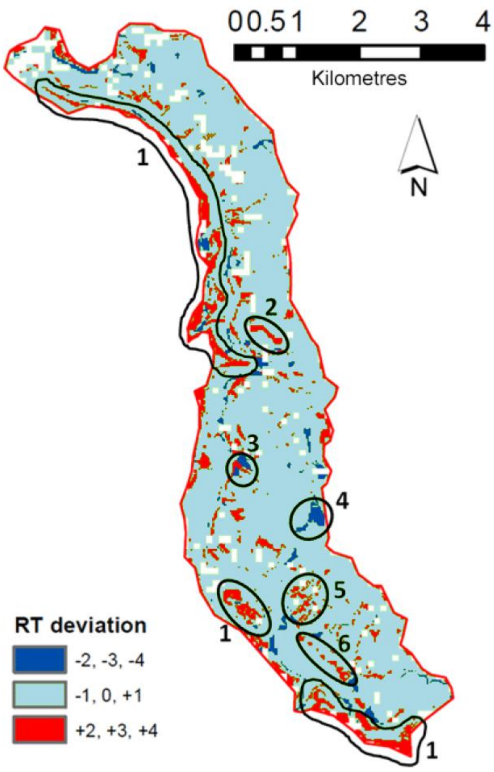

Figure I.8 Deviation map between the MU09 map and the reference map. In the numbered areas the runoff contribution was either overestimated (red) or underestimated (blue).

Figure I.8 shows a map of the Reppisch catchment highlighting areas where the discrepancy between the RTs in the MU09-map and the SN03-map is higher than 2 (Table I.4). The RT assigned to area 1 is too fast as the glacial sediments were assumed to be always impermeable. Similarly, area 3 was mapped as a non-contributing area as the alluvium was assumed to be always permeable. However, previous investigations showed the local permeability of the glacial sediments was high and the one of the alluvium was low due to clayish sediments (Scherrer AG, 2006). Area 2 is located on a steep hillslope and is therefore mapped as contributing with a slight delay. In contrast, area 4 is on a flat plateau, so that its contribution to the runoff was assumed to be

Figure I.9 Agreement scores K_{Fuzzy} and MC scores obtained by comparing the maps derived with automatic mapping approaches SN07, MU09, and GH11 with the reference (SN03) maps for the sub-catchments of the two study areas.

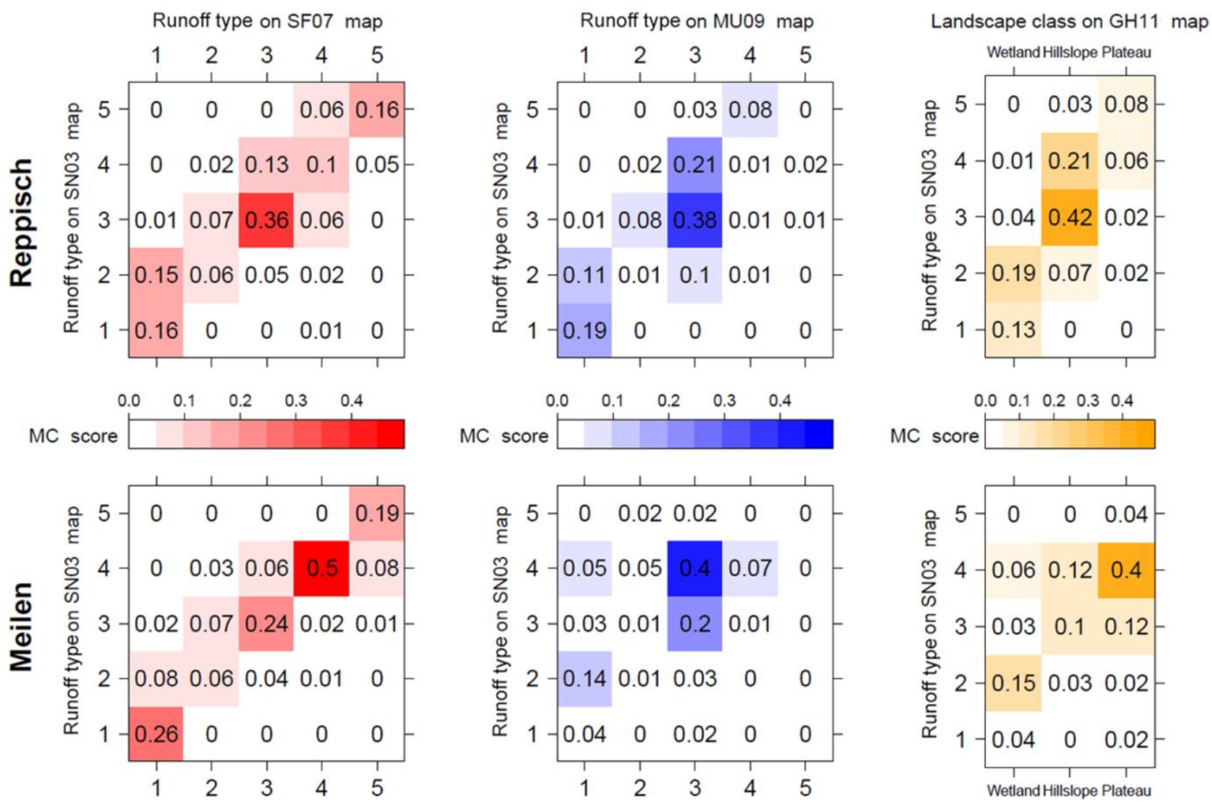

Figure I.10 MC scores related to each RT obtained by comparing the maps derived with automatic mapping approaches SN07, MU09, and GH11 with the reference (SN03) maps for the two study sites.

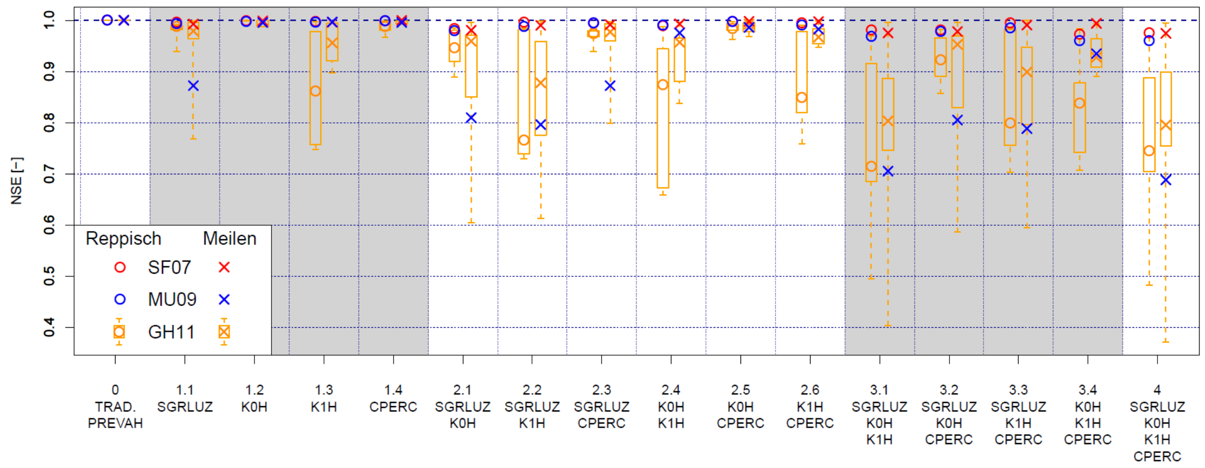

Figure I.11 Modified NSE obtained by comparing the runoff simulated with the automatic DRP maps with that simulated with the reference maps, in the two study sites (simulation period 16 June 2014–15 August 2014). The boxplots show the medians and the interquartile ranges of the simulations driven by GH11 maps, while the labels on the abscissa show the model parameters whose values were defined based on the RTs.

strongly delayed. However, field investigations found the soil was very thick indicating a high storage capacity in area 2. In contrast, the mixture of brown-earth, stagnosol and gleysol resulted in a low storage capacity in area 4 (Scherrer AG, 2006). In area 5, the river network derived with the DTM analysis differs considerably from the actual river path. The runoff contribution there was therefore overestimated by MU09. Similarly, the runoff contribution of area 6 was overestimated because the depiction of the lake was wrong due to the coarse resolution of the land-use map.

The measures of association and agreement obtained by comparing the automatically derived DRP-maps with the reference maps for the sub-catchments of the two study areas differ (Figure I.9). The scores of the SF07-maps are higher than those obtained by the comparison of MU09-maps and GH11-maps with the reference maps. The highest scores in the Reppisch catchment were in sub-catchment 1 due to the presence of a lake, which is mapped as RT1 in every mapping approach. As the values of the MC-score obtained with MU09-maps and GH11-maps are nearly equal, these two mapping approaches seem to be interchangeable for both of the two study areas.

Comparing the MC-scores for each RT reveals which RTs can be clearly identified by the automatic mapping approaches (Figure I.10). The higher MC-scores for classifications with the same number of classes should ideally be located along the main diagonal of the output matrices, meaning that each RT of an automatically derived DRP-map is spatially best associated with its equivalent in the reference map. This is mainly the case for the SF07-maps, with the exception of the fast RT1 and RT2. These are identified as more similar to the next slower RTs of the reference maps. The MU09-maps's overestimation of the general runoff intensity of the whole catchment can be attributed to RT2 and RT4 in the Reppisch catchment and RT1 and RT3 in the Meilen catchment. These were spatially associated with the next slower RTs of the reference map. On both study sites, the landscape classes “wetland”, “hillslope” and “plateau” of the GH11-maps fit best with RT2, RT3 and RT4 of the reference maps, respectively.

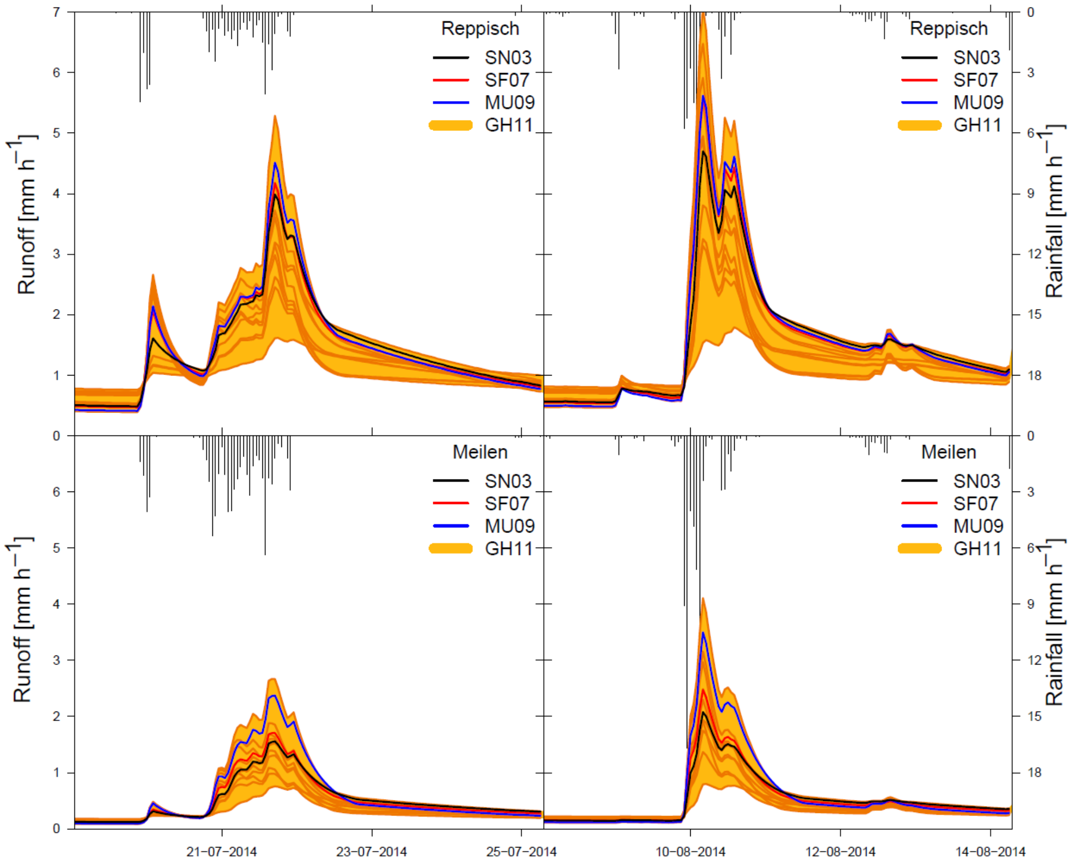

Figure I.12 Simulated runoff during the two heaviest rainfall events of the simulation period, obtained from the different DRP maps for the two study sites by varying the parameter values for each RT (simulation 4.1 of Table A2). The bands represent the minimum and maximum runoff values obtained with the different parameter combinations for the simulations driven by GH11 maps.

Since the extent and distribution of areas with the same RT differ, using automatically derived DRP-maps in runoff simulations affects the results of the simulations themselves (Figure I.11). Simulations driven by the SF07-maps showed the smallest deviation in comparison with simulations driven by the SN03-maps. The tendency of the MU09-maps to overestimate the runoff contribution (Figure I.7) led to higher peaks in the Meilen catchment since overland flow was activated on areas with delayed runoff contribution during the two heavy rainfall events on 21 July 2014 and 10 August 2014 (Figure I.12). This did not happen in the Reppisch catchment as the precipitation intensity in the catchment was lower. The GH11-maps were very sensitive to the storage time for subsurface flow K1H due to the consistency assumption, i.e. no interflow is expected on wetland and plateau areas, which are prone to SOF and DP, respectively. As a result, too much water remained in the storage and runoff peaks were mostly underestimated.

5. Discussion

One of the main purposes of this study was to test how well automatic approaches can map small catchments. The most complex automatic DRP-maps, i.e. the one derived according to Schmocker-Fackel et al. (2007), proved to be most similar to the reference maps derived manually with Scherrer and Naef (2003), according to both the class comparison and the similarities measures. This result is not surprising, considering that the method of Schmocker-Fackel et al. (2007) was developed on the canton of Zurich, where the two study sites are located. However, the method was successfully tested also outside the canton of Zurich (e.g. on the Swiss Prealps, Scherrer et al., 2013).

The DRP-maps derived with simplified mapping approaches, that included no soil information, differed significantly in terms of both extent and distribution of the DRPs from the reference maps. These differences are clearly linked to the quality of the input data. Geological maps are often not fine enough to depict geological formations and possible variations in permeability within the same formation. Furthermore, if the resolutions of the DTM and the land-use map are too coarse, significant biases may result. However, using input data with high resolution would not necessarily improve the results, if the classification concept itself is too coarse and generic. Since topography does not seem to be a good proxy for the storage and infiltration capacity of the soils on the study sites, the approaches developed by Müller et al. (2009) and Gharari et al. (2011) often overestimated the runoff intensity on steep sites and underestimated it on flat sites. These approaches were developed on basins, located in Rhineland-Palatinate (Germany) and in the Grand Duchy of Luxembourg, with different soil properties and event characteristics than those investigated for this study. However, the adaptation of these classifications to the characteristics of our study sites (e.g. by adding or removing input data and modifying the classification criteria accordingly) was beyond the scope of this study.

The high MC-scores obtained by certain pairs of different RTs (Figure I.9), as well as the visual inspection of the DRP-maps, suggest that the perception of the intensity of DRPs varies among different authors. For example, the riparian zones on the reference maps were mostly mapped as RT2, but, where they were completely saturated and at least slightly sloped, they were mapped as RT1. In contrast, on MU09-maps and on SF07-maps the riparian zone was mostly mapped as RT1. Similarly, areas prone to DP on GH11-maps fitted best with RT4 areas of the reference maps, which represent areas where strongly delayed SOF or SSF, but not DP, occur. Since a straightforward, standardised definition of DRPs is missing, not only do the classification criteria vary, but also the classes. This can be misleading, especially if different classes have the same DRP names.

The MC-score ranking of the automatic mapping approaches is similar to the fuzzy kappa ranking, but the differences between the MC-scores were not as significant as those between the fuzzy kappa values (Figure I.9). This is because the degree of association of the maps we compared is moderate. In this case, significant increases of the degree of overlap entail only small increases of the MC-score (see Fig. 1 in Hargrove et al., 2006). This problem was encountered also by Speich et al. (2015).. There is therefore a need for a Goodness-of-Fit score capable of, on one hand, comparing maps with different number of classes and, on the other hand, detecting improvements even if the degree of spatial overlap between maps being compared is moderate.

To keep the rainfall-runoff model as simple as possible strong assumptions had to be made. These included no interception, no evapotranspiration and completely saturated catchments. A calibration against measured runoff would have thus been meaningless. However, recent studies suggest that using expert knowledge in selecting parameter values and introducing constraints can increase the performance of conceptual models even without traditional calibration (Bahremand, 2016; Gharari et al., 2014; Hrachowitz et al., 2014). Therefore, the choice of realistic parameter values according to Viviroli et al. (2009a) and the introduction of parameter constraints allow the simulation results obtained to be plausible. The complexity of the model structure is usually linked to the complexity of the DRP-mapping approaches. Two research directions have recently received attention, one using expert knowledge mainly in the phase of DRP identification (Hellebrand et al., 2011) and the other using this knowledge in the modelling phase (e.g. Gharari et al., 2014; Hrachowitz et al., 2014).

In this study, the same model structure and model constraints were applied to the different DRP-mapping approaches. By doing so, it was possible to investigate the effects of a precise uncertainty source, i.e. the DRP-maps, on the system output, i.e. the simulated runoff, while keeping fixed the other uncertainty sources.

As the results show, the simplified classification approaches mostly fail in representing the spatial localisation of the DRPs and have a large impact on the simulated runoff. This suggests that investing more efforts in the landscape classification could enhance runoff predictions on ungauged catchments by improving the model realism. This will be further investigated during future research, by addressing the uncertainties linked to different input data, model structures, model parameters, and model constraints, as well as their interaction.

6. Conclusions

Mapping DRPs manually produces robust results but is time-consuming. Several ways of mapping DRPs automatically have been developed. They differ in terms of how much input data they require for mapping, their classification criteria, and the number of output classes.

In this study, three approaches to mapping DRPs automatically were compared in two catchments on the Swiss Plateau to determine which produces the most realistic results. The DRP-maps derived automatically with the most complex and most data demanding approach (Schmocker-Fackel et al. 2007) were most similar to the reference maps derived according to the manual approach based on Scherrer and Naef (2003), and resulted in the lowest deviations from them when used as input data for synthetic runoff simulations. The DRP-maps produced using Müller et al.'s (2009) simplified mapping approach, which requires no soil information, and those produced using Gharari et al.'s (2011) topography-based approach differed considerably and similarly from the reference maps in terms of DRPs' extent and distribution. The differences arose from the inaccuracy and the coarse resolution of the input data. The simplifying assumptions these two approaches require also limit their usefulness in automatically mapping small catchments.

The runoff simulations performed with these simplified DRP-maps significantly differed from those performed with the reference maps. It would be therefore worthwhile investing efforts and using expert knowledge to obtain hydrological landscape classifications that are as realistic as possible. A standardised definition of DRPs, moreover, would be helpful to avoid mapping bias due to researchers different perception of DRP intensity.

Author contribution

M. A. and M. Z. designed the comparisons and simulations, while R. B. and M. A. performed them. S. Sch. produced the reference maps, M. M. the SF07-maps, and M. A. and R. B. the MU09-maps and GH11-maps. M. A. prepared the manuscript with contributions from all co-authors.

Acknowledgements

This work was funded through a PhD grant from the Swiss Federal Office for the Environment (FOEN). The meteorological data used as input was provided by the Swiss Federal Office of Meteorology and Climatology MeteoSwiss. Prof. Dr. Peter Molnar supervised the contribution of Rahel Buss. For the calculation of Mapcurve scores, the algorithm available online developed by Dr. Emiel van Loon (University of Amsterdam) was used. We are also grateful to Daniel Farinotti and Anil Yildiz for their helpful comments and feedback, and to Silvia Dingwall for the English revision of the manuscript. We thank Shervan Gharari and another anonymous reviewer for their comments and suggestions on a previous version of the manuscript.

Edited by: M. Weiler

Supporting Material

See Table S1, S2, and S3, as well as Figure S1.

Table S1 Reclassification of the reference maps for the class comparison with the GH11 maps.

Combination	1	2	3	4	5	6
Wetland	RT1	RT1	RT1	RTs 1,2	RTs 1, 2	RTs 1, 2, 3
Hillslope	RT2	RTs 2, 3	RTs 2, 3, 4	RT3	RTs 3, 4	RT4
Plateau	RTs 3, 4, 5	RTs 4, 5	RT5	RTs 4, 5	RT5	RT5

Table S2 Parameter values used for the 16 runs of the synthetic runoff simulations. The simulation names are of the form "i.j ", where i refers to the number of parameters defined based on the RTs and j refers to the different combinations.

Simulation name		0.1	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	2.5	2.6	3.1	3.2	3.3	3.4	4.1
SGRLUZ1	(mm)	30	5	30	30	30	5	5	5	30	30	30	5	5	5	30	5
SGRLUZ2	(mm)	30	15	30	30	30	15	15	15	30	30	30	15	15	15	30	15
SGRLUZ3	(mm)	30															
SGRLUZ4	(mm)	30	100	30	30	30	100	100	100	30	30	30	100	100	100	30	100
SGRLUZ5	(mm)	30	200	30	30	30	200	200	200	30	30	30	200	200	200	30	200
K0H1	(h)	20	20	5	20	20	5	20	20	5	5	20	5	5	20	5	5
K0H2	(h)	20	20	10	20	20	10	20	20	10	10	20	10	10	20	10	10
K0H3	(h)	20															
K0H4	(h)	20															
K0H5	(h)	20															
K1H1	(h)	100	100	100	103	100	100	103	100	103	100	103	103	100	103	103	103
K1H2	(h)	100	100	100	50	100	100	50	100	50	100	50	50	100	50	50	50
K1H3	(h)	100															
K1H4	(h)	100	100	100	150	100	100	150	100	150	100	150	150	100	150	150	150
K1H5	(h)	100	100	100	103	100	100	103	100	103	100	103	103	100	103	103	103
CPERC1	(mmh^{-1})	0.12	0.12	0.12	0.12	0.04	0.12	0.12	0.04	0.12	0.04	0.04	0.12	0.04	0.04	0.04	0.04
CPERC2	(mmh^{-1})	0.12	0.12	0.12	0.12	0.08	0.12	0.12	0.08	0.12	0.08	0.08	0.12	0.08	0.08	0.08	0.08
CPERC3	(mmh^{-1})	0.12															
CPERC4	(mmh^{-1})	0.12	0.12	0.12	0.12	0.16	0.12	0.12	0.16	0.12	0.16	0.16	0.12	0.16	0.16	0.16	0.16
CPERC5	(mmh^{-1})	0.12	0.12	0.12	0.12	0.2	0.12	0.12	0.2	0.12	0.2	0.2	0.12	0.2	0.2	0.2	0.2
CG1H	(h)	600															
SLZ1MAX	(mm)	150															
K2H	(h)	2500															

Table S3 Parameter combinations for the simulations driven by the GH11 maps. ϑ = SGRLUZ, K0H, K1H, CPERC. Subscripted numbers refer to the RTs.

Combination	A	B	C	D	E	F	G	H	I	J
$\vartheta_{WETLAND}$	ϑ_1	ϑ_1	ϑ_1	ϑ_1	ϑ_1	ϑ_1	ϑ_2	ϑ_2	ϑ_2	ϑ_3
$\vartheta_{HILLSLOPE}$	ϑ_2	ϑ_2	ϑ_2	ϑ_3	ϑ_3	ϑ_4	ϑ_3	ϑ_3	ϑ_4	ϑ_4
$\vartheta_{PLATEAU}$	ϑ_3	ϑ_4	ϑ_5	ϑ_4	ϑ_5	ϑ_5	ϑ_4	ϑ_5	ϑ_5	ϑ_5

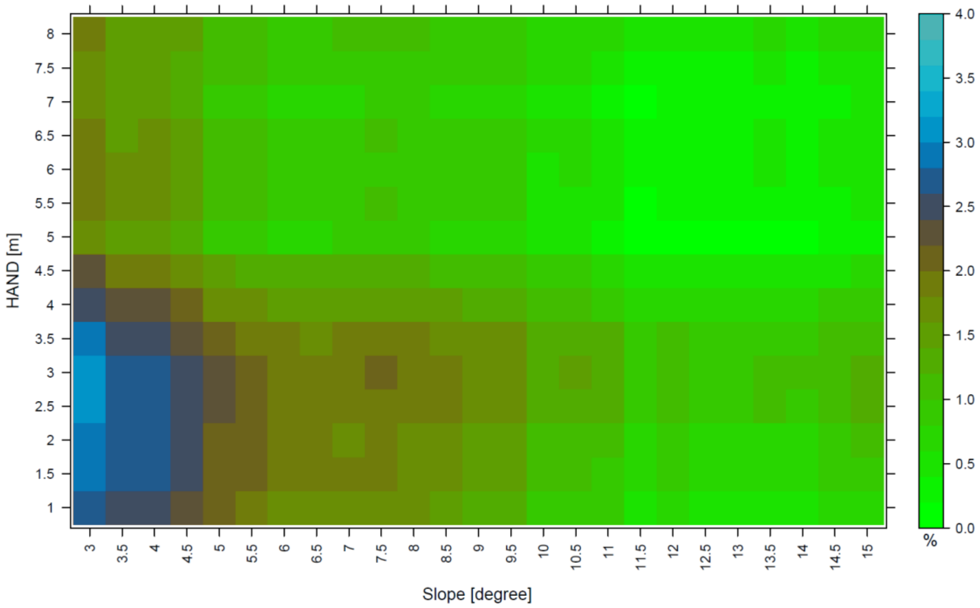

Figure S1 Sensitivity analysis of the threshold values for the HAND-based landscape classification on the whole Reppisch catchment. The level plot shows the percentage of deviation from the maximal MC score (0.2023) obtained by comparing GH11 maps with the reference maps.

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II. Process-based hydrological modelling: The potential of a bottom-up approach for run-off predictions in ungauged catchments

Accepted for publication in Hydrological Processes. Please note that the following text corresponds to that of the accepted article and may slightly differ from the final version of the paper, which was published after the writing of this dissertation.
DOI: 10.1002/hyp.11232.

Manuel Antonetti[a,b], Simon Scherrer[c], Peter Matthias Kienzler[c], Michael Margreth[d], and Massimiliano Zappa[a]

Abstract

Conceptual rainfall-runoff models are a valuable tool for predictions in ungauged catchments. However, most of them rely on calibration to determine parameter values. Improving the representation of runoff processes in models is an attractive alternative to calibration. Such an approach requires a straightforward, a priori parameter allocation procedure applicable on a wide range of spatial scales. However, such a procedure has not been developed yet.

In this paper we introduce a process-based runoff generation module (RGM-PRO) as a spin-off of the traditional runoff generation module of the PREVAH hydrological modelling system. RGM-PRO is able to exploit information from maps of runoff types, which are developed based on field investigations and expert knowledge. It is grid-based and, within each grid cell, the process heterogeneity is considered to avoid information loss due to grid resolution. The new module is event based, and initial conditions are assimilated and downscaled from continuous simulations of PREVAH, which are also available for real-time applications. Four parameter allocation strategies were developed, based on the results of sprinkling experiments on 60 m^2 hillslope plots at several grassland locations in Switzerland, and were tested on five catchments on the Swiss Plateau and Prealps. For the same catchments, simulation results obtained with the best parameter allocation strategy were compared with those obtained with different configurations of the traditional runoff generation module of PREVAH, which was also applied as an event based module here. These configurations include a version that avoids calibration, one that transfers calibrated parameters, and one that uses regionalised parameter values.

RGM-PRO simulated heavy events in a more realistic way than the non-calibrated traditional runoff generation module of PREVAH, and, in some instances, it even exceeded the performance of the calibrated traditional one. The use of information on the spatial distribution of runoff types additionally proved to be valuable as a regionalisation technique, and showed advantages over the other regionalisation approaches, also in terms of robustness and transferability.

[a] Swiss Federal Research Institute WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland.

[b] Department of Geography, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland.

[c] Scherrer AG, Schönmattstrasse 8, 4153 Reinach, Switzerland.

[d] SoilCom GmbH, Probusweg 22, 8057 Zurich, Switzerland.

1. Introduction

Predicting runoff in ungauged catchments is among the most important tasks of hydrologists, given that runoff data is only available for a small percentage of the catchments throughout the world. The techniques developed for this purpose can basically be grouped into statistical and process-accounting methods (Blöschl et al., 2013). Statistical methods establish empirical relationships between catchment characteristics and runoff, and can be based on indexes, regression models or geostatistics (for a review we refer to Blöschl et al., 2013 and Hrachowitz et al., 2013). Rainfall-runoff models, an example of process-accounting methods, are based on the hydrologist's understanding of the catchment and rely on the assumption that, by simulating the runoff processes in a realistic manner, good extrapolation over space and time can be achieved. Physically-based rainfall-runoff models attempt to solve continuity equations (e.g. the Richards equations) by using measurable parameters, which cannot be measured everywhere. In addition, such models are usually computationally expensive and rely on assumptions derived at small scales, that do not necessarily work on the catchment scale (Beven, 2001; Grayson et al., 1992). In contrast, conceptual models are computationally more efficient, but rely on simplified representations of the catchment components and are controlled by parameters, that are not always directly measurable or inferable from the field (McDonnell et al., 2007). Conceptual models therefore need to be calibrated against measured runoff data. In recent decades, a plethora of calibration and optimisation techniques has been developed to optimise the model response by forcing the model parameters to compensate for uncertainties and lack of knowledge (e.g. Beven and Binley, 1992; Gupta et al., 1998; Moradkhani et al., 2005). Given their nature, these uncertainties can change in time and space; this is why, as recently stated by Bahremand (2016), the focus of research should be more on the representation of processes in the model than on parameter optimisation techniques (see also Vinogradov et al., 2011; Semenova and Beven, 2015).

A process-based modelling strategy compatible with conceptual models can be based on the concept of dominant runoff process (DRP, Blöschl, 2001). This concept is built on the hypothesis that, among the different runoff generation mechanisms that may occur at a given location (Hortonian overland flow HOF, saturation overland flow SOF, subsurface flow SSF, and deep percolation DP), there will be one that contributes most to runoff and is therefore the DRP.

Several studies have developed methods for identifying DRPs and models focussed on them. Basically, two strategies can be recognised: the top-down and the bottom-up approach. The first strategy follows the coevolutionary concept expressed by Savenije (2010) and is mainly based on the "height above the nearest drainage" (HAND) metric (Rennó et al., 2008; Gharari et al., 2011). Examples of top-down modelling approaches based on the DRP concept are given in Gao et al. (2014), Gharari et al. (2014), Euser et al. (2015), Fenicia et al. (2016), and Nijzink et al. (2016), and were not investigated further in this study. In the bottom-up approach, the system is first studied at the small scale, typically with field investigations and/or sprinkling experiments. The resulting knowledge is then extrapolated to larger scales (Schmocker-Fackel et al., 2007).

Table II.1 Overview of integration approaches of spatially distributed information on DRP in rainfall-runoff models; TS = Temporal Scale; CO = Continuous; EB = Event-based; HRU = Hydrological Response Unit; RGM = Runoff generation module.

Model	Author(s)	DRP mapping approach	TS	Spatial discretisation	Model structure	Parameter determination
LARSIM	Haag et al., (2016)	Scherrer and Naef (2003)	CO	Grid-based	One parameter set for each HRU	Calibration
LARSIM	Casper et al.(2015); Gronz (2013)	Steinrücken and Behrens (2010)	CO	HRU-based	One parameter set for each HRU	Calibration
QArea	VAW (1994); Horat (2000)	Scherrer and Naef (2003)	EB	HRU-based	One Response Curve for each HRU	A priori definition
QArea-pro	Schmocker-Fackel (2004)	Based on Scherrer and Naef (2003)	EB	HRU-based	One module for each HRU	A priori definition
QArea+	Smoorenburg (2015)	Based on Scherrer and Naef (2003)	EB	HRU-based	One model configuration for each HRU	A priori definition
DIY Model	Dunn et al. (2003)	Boorman et al. (1995)	CO	HRU-based	One parameter set for each HRU	Calibration
-	Hellebrand and van den Bos (2008)	Steinrücken et al. (2006)	CO	HRU-based	One parameter set for each HRU	Calibration
DRP Model	Hellebrand et al. (2011)	Müller et al. (2009)	CO	HRU-based	One RGM for each HRU	Calibration
TAC^D	Uhlenbrook et al. (2004)	Tilch et al. (2002)	CO	Grid-based	Sequentially connected RGMs	Manual calibration
Runoff Coefficient Model	Carver et al. (2009)	Carver et al. (2009)	CO	Grid-based with sub-grid parameterisation of DRPs	One Runoff Coefficient for each HRU	A priori definition
Process Model	Rosin (2010)	Rosin (2010)	EB	Grid-based	One specific combination of RGMs for each HRU	Calibration
KAMPUS (aka Flash Flood Model)	Reszler et al. (2006); Blöschl et al. (2008); Rogger et al. (2012)	Markart et al. (2004)	CO	Grid-based	One parameter set for each HRU	A priori def. (Reszler et al., 2006; Blöschl et al., 2008) Manual Calibration (Rogger et al., 2012)
ZemoKoSt	Kohl and Stepanek (2005)	Markart et al. (2004)	EB	HRU-based	One runoff coefficient for each HRU, calculation of flow times	A priori definition
RoGeR	Steinbrich et al. (2016)	Steinbrich et al. (2016)	EB	Grid-based	One parameter set for each DRP	A priori definition

An overview of the bottom-up approaches based on the DRP concept is given in Table II.1. With regard to the hydrological classification, these approaches are usually based on that of Scherrer and Naef (2003), who developed a classification and decision scheme based on the results of sprinkling experiments and field investigations (Scherrer et al., 2007). Notable exceptions are the hydrological classifications developed based on hillslope genesis (Tilch et al., 2002) or vegetation types (Markart et al., 2004). In some cases, the runoff generation modules of already existing hydrological modelling systems are adapted (e.g. Gronz, 2013; Casper et al., 2015; Haag et al., 2016), while in most cases new runoff generation modules are built for exploiting information on DRPs (e.g. VAW, 1994; Schmocker-Fackel, 2004; Uhlenbrook et al., 2004; Johst et al., 2008; Hellebrand et al., 2011; Smoorenburg, 2015). The spatial distribution of DRPs is considered by defining either a grid-based or an HRU-based spatial discretisation. Concerning the model structure, it is possible to discern between two distinct approaches. In an "one-size-fits-all" approach, the structure of the runoff generation module is fixed and only the parameter set changes for each DRP (e.g. Hellebrand and van den Bos, 2008; Carver et al., 2009; Haag et al., 2016). In contrast, within a flexible framework, both structure and parameter set are developed specifically for each DRP (Hellebrand et al., 2011; Uhlenbrook et al., 2004). According to their scope, DRP-based runoff generation modules and models are designed as either continuous or event-based, depending on whether the evapotranspiration process is simulated rather than estimated from outside information or fixed at a certain rate.

However, nearly all of the models mentioned above rely on calibration for the estimation of parameter values and are therefore not directly applicable to ungauged catchments unless an approach for transferring the parameter values is available (Casper et al., 2015; Dunn et al., 2003; Haag et al., 2016; Hellebrand et al., 2011; Rosin, 2010; Uhlenbrook et al., 2004). Notable exceptions are represented by Blöschl et al. (2008), Steinbrich et al. (2016), and VAW (1994), who performed a logic-based specification of parameter values, from here on referred to as "parameter allocation" (Bahremand, 2015). Blöschl et al. (2008) developed a distributed model for forecasting flash floods in northern Austria. However, their parameter allocation strategy is based on field investigations, runoff data, and piezometric heads of the catchment where the model is applied. The application of their model to a new catchment would therefore require a significant effort to redefine the values of the model parameters. Recently, Steinbrich et al. (2016) developed the RoGeR model for predicting flash-floods in the state of Baden-Württemberg. The model avoids the use of calibration, but, for the parameter allocation, high-resolution data are needed (e.g. soil maps, hydrogeological maps). Furthermore, the particularly high spatial and temporal resolution of the model reduces its applicability to large mesoscale catchments. QAREA is an event-based rainfall-runoff model developed in Switzerland (VAW, 1994). It is based on response curves, obtained from idealised results of sprinkling experiments, for the partitioning of rainfall into fast and slow runoff components (for more details we refer to Smoorenburg, 2015). Its parameterisation makes QAREA particularly suitable for transferability to other catchments, provided that the spatial distribution of DRPs is known. However, the requirement to define the initial conditions in QAREA is problematic, and the model is not able to directly exploit spatially distributed information on soil moisture.

A DRP-based modelling framework able to achieve both a high computational efficiency and a wide applicability over different spatial scales is still lacking. Therefore, the objectives of this paper are to (i) introduce a new process-oriented runoff generation module (RGM-PRO) able to use information on the spatial distribution of DRPs; (ii) evaluate different strategies for its a priori parameter allocation and (iii) compare its performance with that of a traditional conceptual runoff generation module (RGM-TRD) when applied to ungauged catchments.

In this paper, we present a process-based spin-off of the runoff generation module of the PREVAH hydrological modelling system (Gurtz et al., 2003; Zappa and Gurtz, 2003; Viviroli et al., 2009b). Four parameter allocation strategies developed based on the results of sprinkling experiments are evaluated, and the best one is used to compare the results of RGM-PRO with those of different configurations of RGM-TRD on several catchments.

2. Data and methods

2.1 Sprinkling experiments and study catchments

The use of sprinkling experiments is fundamental for gaining knowledge about the processes occurring at the plot scale (Scherrer and Naef, 2003) and for trying to upscale this knowledge with a rainfall runoff model (e.g. Schindewolf and Schmidt, 2009; Dobmann, 2010; Kohl et al., 2016). For this paper, the results of 12 sprinkling experiments performed in eight sites in Switzerland by Scherrer (1997) and Kienzler (2007) were available (Table II.2, Figure II.1). Precipitation at rates of 20 – 100 mm/h was applied on 60 m^2 hillslope plots for durations between 3 and 6 hours. The generated overland flow, near surface flow and subsurface flow were gauged. Also, soil moisture, soil-water suction and soil water table were measured. Sites were selected to cover a broad range of conditions with respect to geology, soil characteristics and topography. Each individual site was selected as homogeneous as possible within the plot to facilitate the determination of the DRP. For more details on the sprinkling experiments we refer to Scherrer et al. (2007) and Kienzler and Naef (2008). Selected sprinkling experiments were simulated by Faeh et al. (1997), who numerically solved the 2 dimensional Richard's equations with the physically-based model QSOIL. Recently, Steinbrich et al. (2016) simulated a subset of the same sprinkling experiments with the a priori parameterised RoGeR model. Their results were used as basis for comparison within the present study.

For this study, runoff simulations were performed for several catchments located in Switzerland (Figure II.1). The Sperbelgraben and the Rappengraben are located close to each other in the Emmental region, canton of Bern. They are similar in terms of area (about 0.5 km^2), geology (Molasse with conglomerate layers), soil type (mainly cambisol) and topography (steep slopes), while they differ considerably in terms of forest coverage. While forest completely covers the Sperbelgraben, only about the half of Rappengraben is covered by forest and the remaining part is used as pasture (Stähli et al., 2011).

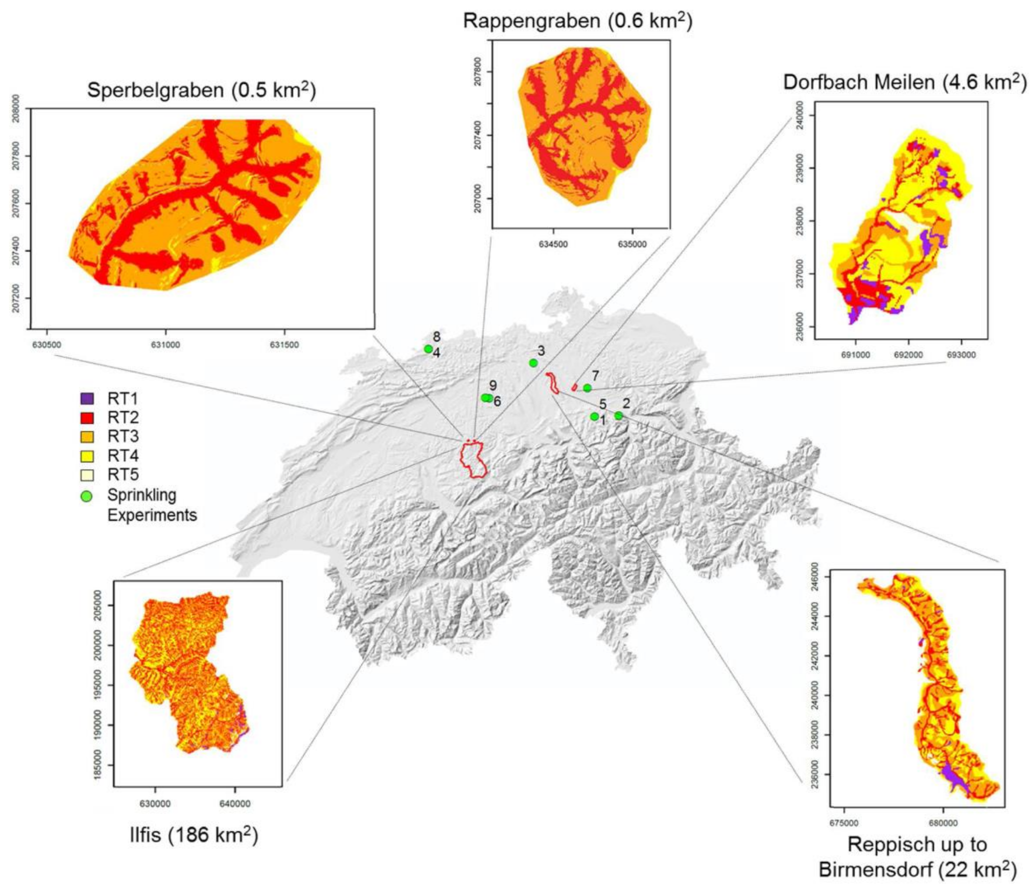


Figure II.1 Overview of the location of the sprinkling experiments, the five study catchments and their maps of runoff types (data: Federal Office of Topography swisstopo).

The catchment of Dorfbach Meilen (4.6 km^2) and that of the Reppisch up to Birmensdorf (22 km^2) are both located on the Swiss Plateau (Antonetti et al., 2016a). Both catchments are mainly covered by grassland and forest and, to a lesser extent, arable land and settlements, and they are characterised by the Upper Freshwater Molasse with conglomerate in the shallow subsurface (Bolliger, 1999; Hantke, 1967; Pavoni et al., 1992). Cambisols with normal permeability and storage capability cover most of the catchments, while soils with low permeability are less widespread. The Ilfis catchment (188 km^2) is located in the upper Emmental and Entlebuch regions in the cantons of Bern and Lucerne. Nearly half of the catchment is forested, whereas the remaining part is mainly covered by arable land and meadow. The northern part of the catchment is characterised by conglomerates of Upper Freshwater Molasse (i.e. Napf-Nagelfluh), with a normal to low conductivity, whereas a low permeable subalpine Molasse and Flysch can be found in the south-eastern part of the catchment. Cambisol and Regosol are the most widespread soils in the catchment.

Table II.2 Details of the sites where data from sprinkling experiments are available. Adapted from Scherrer et al. (2007) and Kienzler and Naef (2008). LS = Landscape; PA = Prealps; SP = Swiss Plateau; URP = Upper Rhine Plain; VC = Vegetation Cover; m: meadow, p: pasture, f: forest.

No.	Location	LS	Soil classification	Parent Material	VC	Slope [%]	DRP according to Scherrer and Naef (2003)
1	Willerzell (sink)	PA	Humic gleysol	Sandstone-colluvium	p	36	SOF1
2	Bilten	PA	Humic gleysol	Conglomerate	f	31	SOF1
3/1	Heitersberg	SP	Eutric cambisol	Moraine	m	27	HOF1
3/2	Heitersberg	SP	Eutric cambisol	Moraine	m	27	HOF1
4	Therwil	URP	Luvisol	Sandstone-shale	m	23	SOF2
5/1	Willerzell (hillslope)	PA	Ranker	Sandstone	p	55	SSF2
5/2	Willerzell (hillslope)	PA	Ranker	Sandstone	p	55	SSF2
6	Lutertal	SP	Cambisol	Siltstone of "Oeningien" Molasse	m	30	SSF2
7	Schlüssberg	PA	Calcaric cambisol	Ground moraine	m	28	SSF3
8/1	Therwil	URP	Luvisol	Sandstone-shale	m	23	SOF3
8/2	Therwil	URP	Luvisol	Sandstone-shale	m	23	SOF3
9	Reiden	SP	Cambisol	Sandstone of "Helvetien" Molasse	m	40	SSF3-DP

Table II.3 Reclassification of DRPs according to RTs (HOF = Hortonian Overland Flow; SOF = Saturation Overland Flow; SSF = Subsurface Flow; DP = Deep percolation; 1 represents an almost immediate reaction, 2 a slightly delayed one and 3 a strong delayed one). Adapted from Naef et al. (2000).

Runoff type (RT)	DRP	Runoff intensity
1	HOF1/2, SOF1	Fast
2	SOF2, SSF1	Slightly delayed
3	SSF2	Delayed
4	SOF3, SSF3	Strongly delayed
5	DP	Not contributing

2.2 The process maps

The runoff processes in the study catchments were mapped based on the decision schemes of Scherrer and Naef (2003), which allow the DRP to be determined at the plot scale based on the hydrological properties of the surface and the soil. Information on the process intensity is provided with a number from "1" to "3" beside the DRP, where "1" represents an almost immediate reaction, "2" a slightly delayed one and "3" a strongly delayed one. However, interactions between different DRPs on a given hillslope profile ("process catena"; Schmocker-Fackel et al., 2007) and the connectivity of an area to the river network can significantly influence the contribution to runoff of a given area. During the mapping, therefore, the information about the DRPs at the plot scale is scaled up to the catchment scale and the DRPs are reclassified into five classes (called "runoff types") according to the intensity of the contribution to runoff. For this study, two upscaling methods were used for scaling up the DRPs from the plot to the catchment scale: the manual method described in Scherrer AG (2006) and the automatic one based on Schmocker-Fackel et al. (2007). The first method is based on expert knowledge and is performed manually. The second approach is an enhancement of Scherrer AG (2006) and relies on soil maps with a high resolution and on the conversion criteria reported in Table II.3. Where information on soil is unavailable, the expert-based soil prediction model of Margreth et al. (2010) is used. Basically, the two methods differ from each other in terms of time required for upscaling. Whilst several days of fieldwork are necessary for the manual mapping of an area, the most time-expensive step of the automatic method is its configuration for a new basin, which depends on the available information. However, some days of fieldwork are also necessary for the automatic approach, as the algorithm needs to be first calibrated against manually derived maps on a few small test areas and then validated at selected locations within the catchment (Margreth et al., 2010). This procedure makes the automatic method more attractive for large areas than the manual one. Therefore, the process map of the largest study catchment (Ilfis, 186 km^2) was derived with the automatic approach of Schmocker-Fackel et al. (2007), whereas manually derived maps were available for the catchments Reppisch and Dorfbach Meilen from a previous study (Antonetti et al., 2016a). Given their proximity to the Ilfis catchment, also Sperbelgraben (0.5 km^2) and Rappengraben (0.6 km^2) were mapped with the automatic approach. Antonetti et al. (2016) compared the two methods and found that the automatic mapping approach of Schmocker-Fackel et al. (2007) yields the most similar results to those of Scherrer AG (2006) in terms of extent and distribution of RTs. For a more detailed description of the mapping approaches and their differences we refer to Antonetti et al. (2016a).

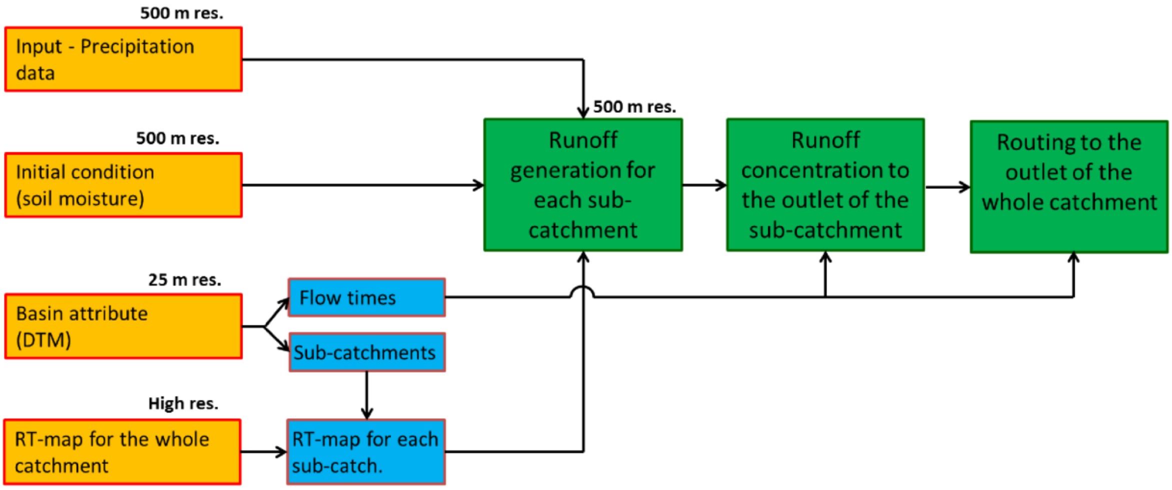


Figure II.2 Flow diagram of the configuration of RGM-PRO used in this study.

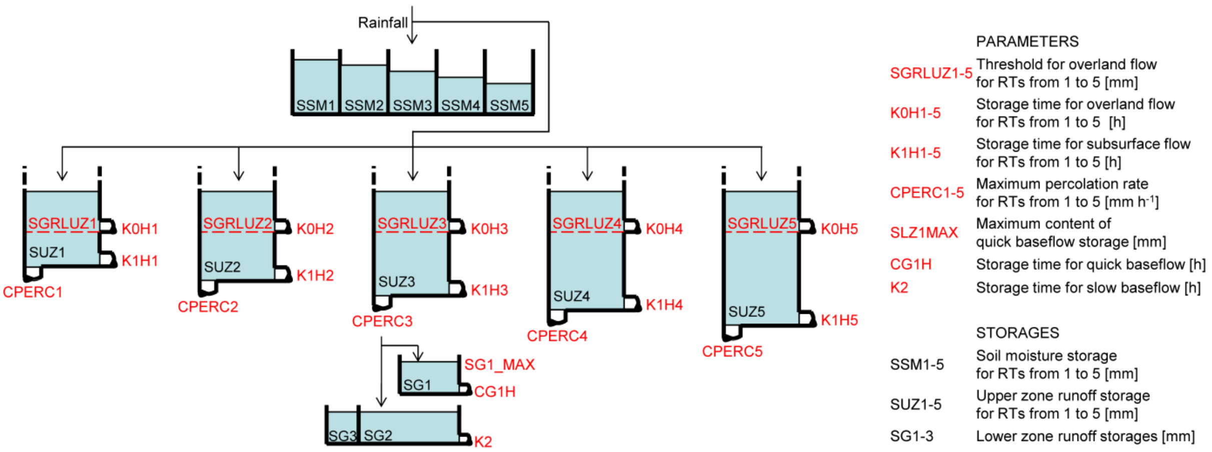


Figure II.3 Schematic representation of the structure of RGM-PRO.

3. The process-based runoff generation module RGM-PRO

RGM-PRO is a further development of the runoff generation module used by Antonetti et al. (2016b). For its use, information on the spatial distribution of runoff types and spatially distributed rainfall data need to be provided (Figure II.2). RGM-PRO is event-based, meaning that, for its initialisation, it needs information on the antecedent wetness conditions of the catchment, which could potentially be provided by any grid-based hydrological model or even measured (e.g. Parajka et al., 2005). For this study, the plant available soil moisture was assimilated from grid-based simulations of the PREVAH hydrological modelling system (section 6.3.3.).

3.1 Configuration

Based on a DTM with a 25 m resolution, each study catchment was divided into sub-catchments up to 2 km^2 in size with the Topographic Analysis Tool (TANALYS; Schulla, 1997). The runoff generation was therefore computed for each sub-catchment. To do this, a grid based discretisation was chosen with a grid size of 500 m × 500 m, and a specific configuration was designed to deal with both the spatial variability of the rainfall data and the spatial heterogeneity of the runoff types. To account for the sub-grid variability of the runoff types, the percentage of each runoff type within each grid cell was first calculated. The runoff was then calculated for each cell as if there were one single runoff type for the entire cell. The total runoff was finally calculated as a weighted average. This approach limits computational effort while avoiding information loss due to grid resolution and has already been adopted by Carver et al. (2009) and Nijzink et al. (2016).

The runoff concentration to the outlet of the sub-catchment is then calculated for both overland flow and subsurface flow. For the first, the flow times calculated with TANALYS are considered; for the second, a linear storage with one storage constant is used. The outflow of each sub-catchment is finally routed to the main outlet according to the flow times calculated with a Strickler coefficient of 30 m$^{1/3}$ s^{-1} (Schulla, 1997).

3.2 Structure

The structure of RGM-PRO is based on that of the traditional runoff generation module of PREVAH (Gurtz et al., 2003; Zappa and Gurtz, 2003; Lehning et al., 2006), which follows, in turn, the ideas governing the runoff generation of the HBV model (Bergström, 1976). It consists of a plant available soil moisture storage, a storage system for the runoff generation controlled by four parameters for each runoff type, and the same groundwater storage as in RGM-TRD (Gurtz et al., 2003; Figure II.3). The precipitation can either go into the plant available soil moisture storage (SSM1-5) or enter directly into the runoff generation storages (SUZ1-5). A non-linearity parameter BETA set equal to 3 controls the partitioning of water between the soil moisture storages and the runoff generation modules, where the storage times for the surface runoff (K0H1-5) and subsurface runoff (K1H1-5) regulate the generation of the runoff. The thresholds for quick runoff formation (SGRLUZ1-5) determine the separation between surface and subsurface runoff. Maximum percolation rates (CPERC1-5) control the percolation to the groundwater storage. This is divided into a quick-leaking storage (SG1) and two slow-leaking storages (SG2 and SG3) and is controlled by three parameters (SLZ1MAX, CG1H and K2H). For a more detailed description of the groundwater storage system we refer to Viviroli et al. (2009b) and Schwarze et al. (1999).

3.3 Assimilation and downscaling of soil moisture

One of the problems of event-based models is the definition of initial conditions. For this study, the plant available soil moisture was assimilated from grid-based simulations of PREVAH with a resolution of 500 m. These simulations have been computed in real-time since 2012 for the whole of Switzerland as part of the http://www.drought.ch platform (Zappa et al., 2014; last access: 2.12.2016). Retrospective simulations and initial conditions are available for the period 1981 to 2016. Because the spatial variability of the soil moisture is higher than the resolution of the PREVAH simulations, the downscaling technique described in Blöschl et al. (2009) was applied. This method relies on three basic assumptions:

- The soil moisture pattern at the smaller scale is time invariant;
- The spatial variance of soil moisture at the smaller scale is linked with that at the larger scale by a scaling theory;
- Soil moisture is mass conserving.

The first assumption allows a static pattern (called fingerprint) to be used. In this study, the process maps were used as fingerprints because they already include information about the spatial distribution of soil moisture (Scherrer et al., 2007). As a consequence of the second assumption, the spatial variance of soil moisture at the smaller scale (σ_S^2) was linked to that at the larger scale (σ_L^2) based on following scaling theory:

$$\sigma_S^2 = \sigma_L^2 \cdot \left(\frac{L_S}{L_L}\right)^{-\alpha} \qquad \text{Eq. 1}$$

where L_S and L_R are the length scales (i.e. the grid sizes) and α is an empirical exponent set equal to 0.35 according to Blöschl et al. (2009). Owing to the last assumption, the mean soil moisture at the smaller scale was forced to be equal to the mean soil moisture at the larger scale. After the soil moisture was downscaled to a resolution of 25 m, it was successively re-aggregated to obtain an averaged value for each runoff type for each grid cell.

Table II.4 Plausible parameter ranges defined a priori for each RT.

<table>
<tr><th>RT (DRPs)</th><th>SGRLUZ [mm]</th><th>K0H [h]</th><th>K1H [h]</th><th>CPERC [mm/h]</th></tr>
<tr><td>1 (SOF1, HOF)</td><td>0 - 40</td><td rowspan="5">0.05 -0.4</td><td>1000</td><td rowspan="2">0.1</td></tr>
<tr><td>2 (SOF2, SSF1)</td><td rowspan="2">40 - 100</td><td>0.5 - 2</td></tr>
<tr><td>3 (SSF2)</td><td rowspan="2">2 - 4</td><td>0.1 – 0.5</td></tr>
<tr><td>4 (SOF3, SSF3)</td><td>100 - 200</td><td>0.5 - 5</td></tr>
<tr><td>5 (DP)</td><td>> 200</td><td>1000</td><td>5 - 50</td></tr>
</table>

4. A priori parameter allocation of RGM-PRO

4.1 Defining plausible parameter ranges

Based on the results of the sprinkling experiments mentioned in section 2.1, on physical properties of soils, and on the field expertise of the authors who mapped the runoff types in the investigated areas, plausible value ranges were defined a priori for each parameter of RGM-PRO (Table II.4). With regard to the storage capacity of soils, the values observed during the field observations ranged from 8 to 240 mm (Kienzler, 2007; Scherrer, 1997; Schmocker-Fackel, 2004). The evaluation of the falling limb of the hydrograph of the sprinkling experiments allowed experimentally observed storage constants to be determined. For the overland flow (K0H1-5), values between 0.05 h and 0.4 h were obtained. With regard to the subsurface storm flow, a value around 0.5 h for SSF1 and between 2 h and 4 h for SSF2 and SSF3, respectively, were considered plausible. Concerning the percolation rates, a wide range, from 0 to 90 mm/h, was observed from the SEs. With regard to the runoff concentration, the storage constant of the linear storage for the concentration of subsurface flow was set to values between 1 and 3 h. These values are in agreement with those of Reszler et al. (2006), who completed an a priori parameter allocation of the KAMPUS model.

4.2 Strategies for parameter allocation

Four strategies for the parameter allocation of RGM-PRO were designed and can be grouped into those based on the sprinkling experiments and those based on the runoff types (Figure II.4). In the first case, the basic idea was to select a single sprinkling experiment to represent the whole runoff type, according to Table II.3. Once one representative sprinkling experiment was chosen for each runoff type, the initial ranges described in the previous section were assigned to each of the four parameters of RGM-PRO (SGRLUZ, K0H, K1H, CPERC), according to its DRP and runoff type. For example, because the sprinkling experiment 5/2 (Willerzell – hillslope) is characterised by SSF2, it was selected to represent runoff type 3. An initial range of 40 to 100 mm was therefore assigned to SGRLUZ3, 0.05 to 0.4 h to K0H3, 2 to 4 h to K1H3 and 0 to 50 mm/h to

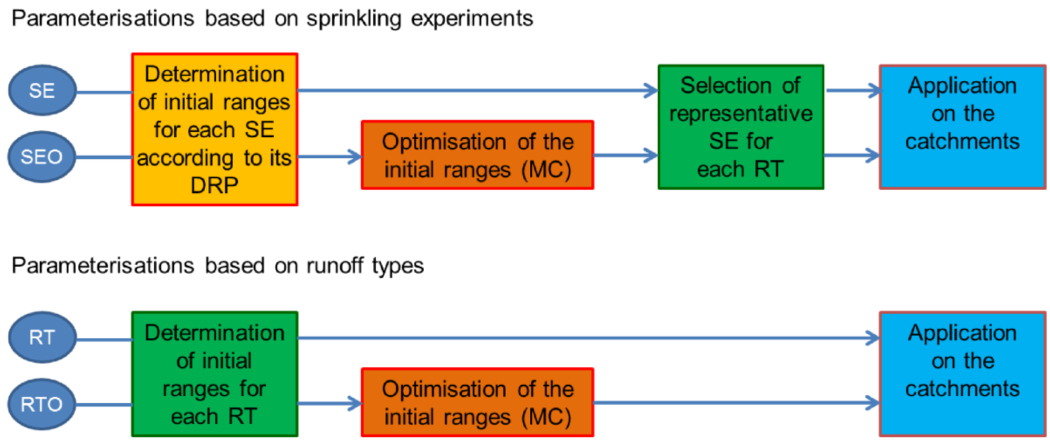


Figure II.4 Schematic representation of the four parameterisation strategies of RGM-PRO. SE = sprinkling experiment; SEO = sprinkling experiment – optimised; RT = runoff type; RTO = runoff type – optimised; MC = Monte Carlo Simulation.

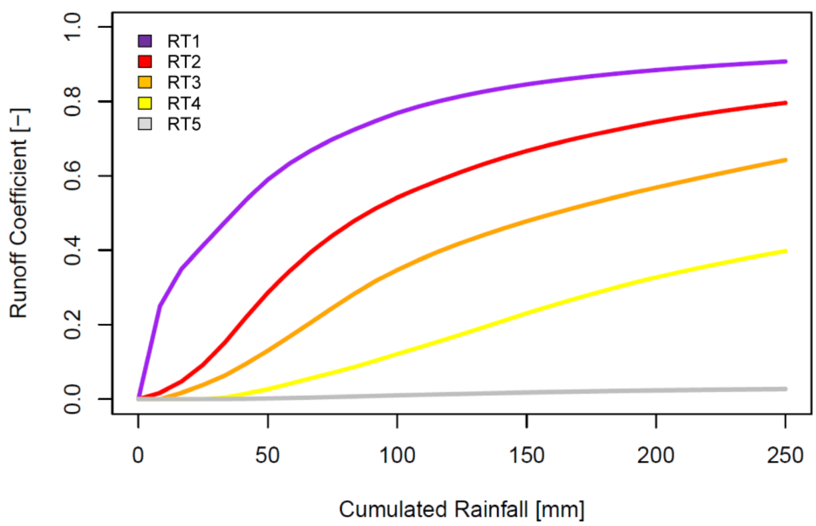


Figure II.5 Response curves of the five runoff types (RTs) as defined by VAW (1994).

CPERC3. Where HOF or DP was expected, the subsurface flow was neglected by setting K1H to a high value (1000 h). Four possible combinations of representative sprinkling experiments were tested (Table II.4). In the second strategy based on the sprinkling experiments, the initial ranges were further constrained by considering only the parameter values which led to the best 1% of a Monte Carlo simulation with 10,000 runs. As objective function, the averaged value of the Nash-Sutcliffe-Efficiency (Nash and Sutcliffe, 1970), calculated against observations of both overland and subsurface flow during the sprinkling experiment, was considered.

The second group of strategies is based on the response curves of the runoff types (Figure II.5; VAW, 1994). These curves are idealised results from the sprinkling experiments and represent the expected behaviour of the correspondent runoff type in terms of intensity to runoff contribution. In the first case, the initial ranges of each model parameter were defined a priori for each runoff type, according to the characteristics of the DRPs belonging to it (Table II.3). With regard to the partitioning of runoff within those runoff types, where different DRPs can occur (e.g. runoff type 2, where both SOF2 and SSF1 can take place; see Table II.3), the parameter ranges were defined in a manner that

Table II.5 The four different combinations of SEs selected to represent one of the five RTs.

	SE	SE1	SE2	SE3
RT1	2	1	2	1
RT2	3/1	3/1	1	2
RT3	5/2	5/2	5/2	4
RT4	7	7	7	8/1
RT5	9	9	9	8/2

allows equifinal combinations to be considered (Beven, 2006). As a result, overland flow and subsurface flow can be partitioned in different ways, provided that the total contribution to runoff reflects that of the correspondent response curve. By doing so, the successful simulation of each sprinkling experiment is not guaranteed anymore because the response curves of the runoff types are referred to the total runoff. In the second configuration, similarly to the strategies based on the sprinkling experiments, the ranges were optimised against the characteristic response curve of each runoff type, by considering only the 1% best runs of a Monte Carlo simulation with 10,000 runs. Since response curves instead of hydrographs are used for the optimisation, the root mean square error (RMSE) was used instead of NSE as objective function.

RGM-PRO was therefore applied to the five study catchments with these four different sets of initial ranges. The set leading to the best results was used for the comparison with RGM-TRD.

5. Comparison of runoff generation modules

RGM-PRO was tested on the study catchments for the long-lasting rainfall events listed in Table II.6. These events were chosen mainly during the summer period to avoid snow related processes that can interfere with the different runoff processes. As input data, a combination of measured rainfall data and radar data with an hourly resolution was used (Sideris et al., 2014). At the beginning of each simulation, the plant available soil moisture was assimilated from grid-based simulations of the traditional PREVAH with a resolution of 500 m, and downscaled according to Blöschl et al. (2009). To gain an insight into the parameter uncertainty, RGM-PRO was run with 10 different combinations of parameter values, which were randomly selected within the ranges defined a priori. The value distribution within each range was assumed to be uniform.

The results obtained with RGM-PRO were compared with those obtained with different configurations of RGM-TRD. These configurations are described in the following text, and an overview is given in Table II.7. Basically, two issues were investigated. First, whether using information on the spatial distribution of runoff types within a catchment is actually advantageous for hydrological simulations. Second, whether the bottom-up approach introduced in this paper can be used in a regionalisation framework, assuming that, once a module structure and its parameters have been determined for each runoff

Table II.6 Start and end of the simulated precipitation events.

Ilfis, Sperbelgraben and Rappengraben			Reppisch and Meilen		
Name	Simulation start	Simulation end	Name	Simulation start	Simulation end
Aug05	01.08.2005	31.08.2005	Aug05	01.08.2005	31.08.2005
Sep06	15.09.2006	30.09.2006	Jun13	30.05.2013	14.06.2013
Aug07	18.07.2007	17.08.2007	Jul14	09.07.2014	16.07.2014
Aug10	20.07.2010	09.08.2010	Jun15	14.06.2015	17.06.2015
Jun12	01.06.2012	20.06.2012	Jun16	08.06.2016	23.06.2016
Sep12	23.08.2012	18.09.2012			
Aug14	21.07.2014	20.08.2014			
May16	11.05.2016	18.05.2016			

type (Figure II.4), they can be transferred to an ungauged catchment where the same runoff type occurs (Beran, 1990; Antonetti et al., 2016a).

To test the first hypothesis, the simulation results obtained with RGM-PRO were compared with those obtained with two configurations of RGM-TRD. In the first case (TRD-2000), a Monte Carlo simulation with 2000 runs was performed for each catchment and for each rainfall event. By doing so, the simulation ability of RGM-TRD on each study catchment was investigated. In addition, by focussing exclusively on the best runs of the same Monte Carlo simulation, insight was gained into whether the a priori parameterised RGM-PRO can lead to better results compared with the calibrated RGM-TRD. In the second configuration (TRD-1st10), similarly to what was done for RGM-PRO, only the first ten runs of the above mentioned Monte Carlo simulation were considered. This allowed the parameter uncertainty of RGM-PRO and the one of the uncalibrated RGM-TRD to be compared.

To test the transferability of RGM-PRO, its simulation results were compared with those from two other typical regionalisation techniques. In the TRD-ParTrans configuration, RGM-TRD was first calibrated on a specific catchment during a single event. The best ten parameter sets were then transferred in space and time to the other catchments. The robustness of this configuration was additionally investigated by varying the donor catchments and the calibration events with a leave-one-out cross-validation. In a different configuration, from here on referred to as TRD-RHQ, the RGM-TRD was fed with the regionalised parameter found by Viviroli et al. (2009a), who developed a parameter regionalisation scheme based on the results of 140 calibrated catchments for flood prediction in ungauged catchments. RGM-TRD was therefore adapted to cope with the spatial heterogeneity of the model parameters.

To guarantee a fair comparison between the runoff generation modules, the interception storage of the configurations of RGM-TRD was switched off, since the interception process is not reproduced by RGM-PRO. In their original study, Viviroli et al. (2009a) calculated a spatially distributed adjustment factor for precipitation, ranging from –30 to +30%. However, this factor was not applied to TRD-RHQ.

Table II.7 Overview of the comparison between RGMs. MC = Monte Carlo simulation; RT = Runoff Type.

	TRD-2000		TRD-1st10	TRD-ParTrans	TRD-RHQ	RGM-PRO
Scope of the Comparison	Testing the added value of process-based hydrological modelling			Testing the transferability to ungauged catchments		
Precipitation Data	CombiPrecip (Sideris et al., 2014)					
Spatial and Temporal Res.	1 km; 1h					
Soil Moisture Data	PREVAH real-time simulations (Zappa et al., 2014)					
Spatial and Temporal Res.	500 m; 1 h					Within each grid cell, one value for each RT (Blöschl et al., 2009)
Parameters	One set for the whole catchment				One set each grid cell	One set each RT
Calibration	NO	YES	NO	YES	YES	NO
Sampling Strategy	All 2000 runs from MC	Best 10 runs from MC	First 10 runs from MC	Best 10 runs from MC on Sperbelgraben – Sep06	Viviroli et al. (2009a)	First 10 runs from MC
Parameter Ranges	From Viviroli et al. (2009a)					From expert knowledge and opti-mised against RTs

5.1 Objective Functions

Model simulations are evaluated with a specific focus on simulated peak runoff and total event volume. Since the traditional Nash-Sutcliffe Efficiency (Nash and Sutcliffe, 1970) does not give exhaustive information about the error nature, the Kling Gupta Efficiency (KGE; Gupta et al., 2009) was used for this study:

$$\mathrm{KGE} = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2} \qquad \text{Eq. 2}$$

where r represents the correlation between simulated and measured runoff, α is the ratio between the standard deviation of the simulated runoff and that of the measured runoff, and β is the ratio of the mean simulated to mean observed discharge.

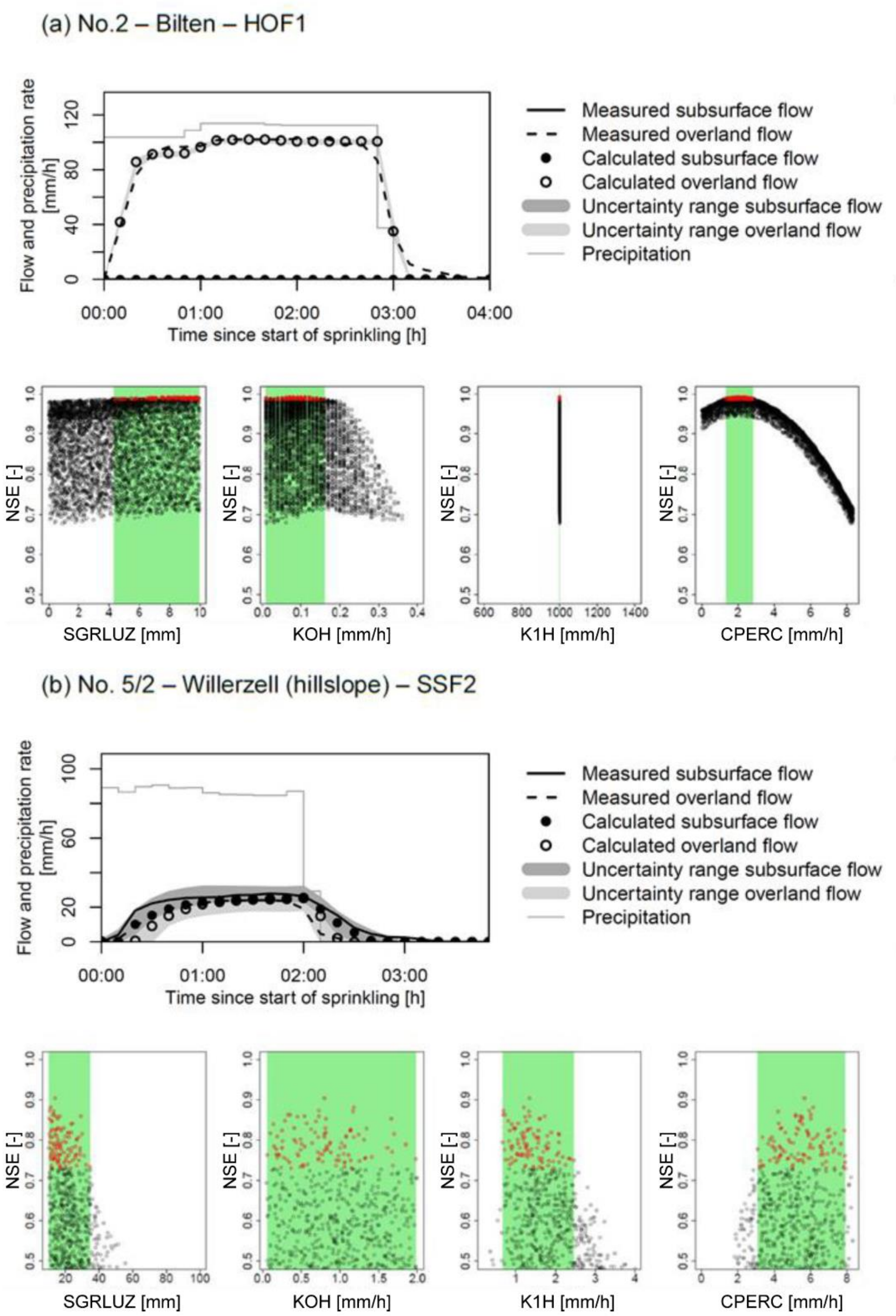


Figure II.6 Hydrographs and dot plots obtained from the simulation of sprinkling experiment no. 2 (Bilten; a) and no. 5/2 (Willerzell, hillslope; b) with RGM-PRO. The red dots in the dot plots refer to the best 1% of a Monte Carlo simulation with 10,000 runs, and the green rectangles highlight the optimised parameter ranges.

In addition, the Series Distance (Ehret and Zehe, 2011) method was used to evaluate the temporal and volumetric shift between simulated and measured hydrographs. Recently, this metric was further developed by Seibert et al. (2016), who introduced an algorithm for a scale-independent definition of hydrographs and a concept for taking uncertainty into account. However, since our study was designed prior to publication of that work, the innovations of Seibert et al. (2016) were not used to evaluate our simulations.

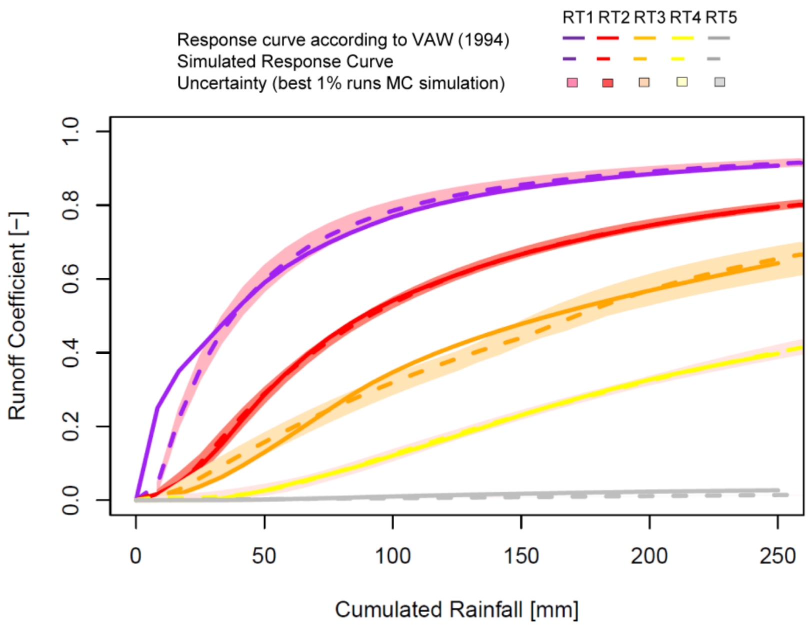


Figure II.7 Simulated response curves and hydrographs for the five runoff types (RTs).

6. Results

6.1 Best option for the a priori parameter allocation

The initial ranges defined a priori based on expert knowledge allowed RGM-PRO to successfully simulate the overland and the subsurface flow of the sprinkling experiments (Figures II.6 and S1) and the response curves of the runoff types (Figures II.7 and S2). In the case of Bilten (Figure II.6a), the most sensitive parameter was the maximum percolation rate CPERC. However, CPERC values between 1.5 and 2.5 mm/10min, although allowing the overland flow to reach the measured steady runoff coefficient (i.e. the ratio between runoff and precipitation) of ca. 0.9, are definitely too high for a HOF1 site. In Willerzell hillslope (Figure II.6b), the threshold for the activation of overland flow SGR-LUZ was the most sensitive parameter, and values smaller than 30 mm, together with high percolation rates, allowed the measured hydrographs to be well reproduced.

The successful reproduction of the sprinkling experiments did not guarantee that the hydrographs of the study catchments were well simulated. During the event between the 12th and the 15th of May 2016 on the Ilfis catchment, for example, the simulated hydrographs showed a higher smoothness compared with the observed one, independently from the parameter allocation strategy used. However, the strategies based on the sprinkling experiments underestimated both the runoff peaks and the runoff volume, while the ones based on the response curves of the runoff types performed better (Figure II.8a). The same tendency was observed for the other catchments and events, and the selection of different representative sprinkling experiments for one or more runoff types did not change the result (Figure II.8b). The strategy optimised against the response curves performed slightly better than that without optimisation, and was therefore chosen for the comparison with RGM-TRD.

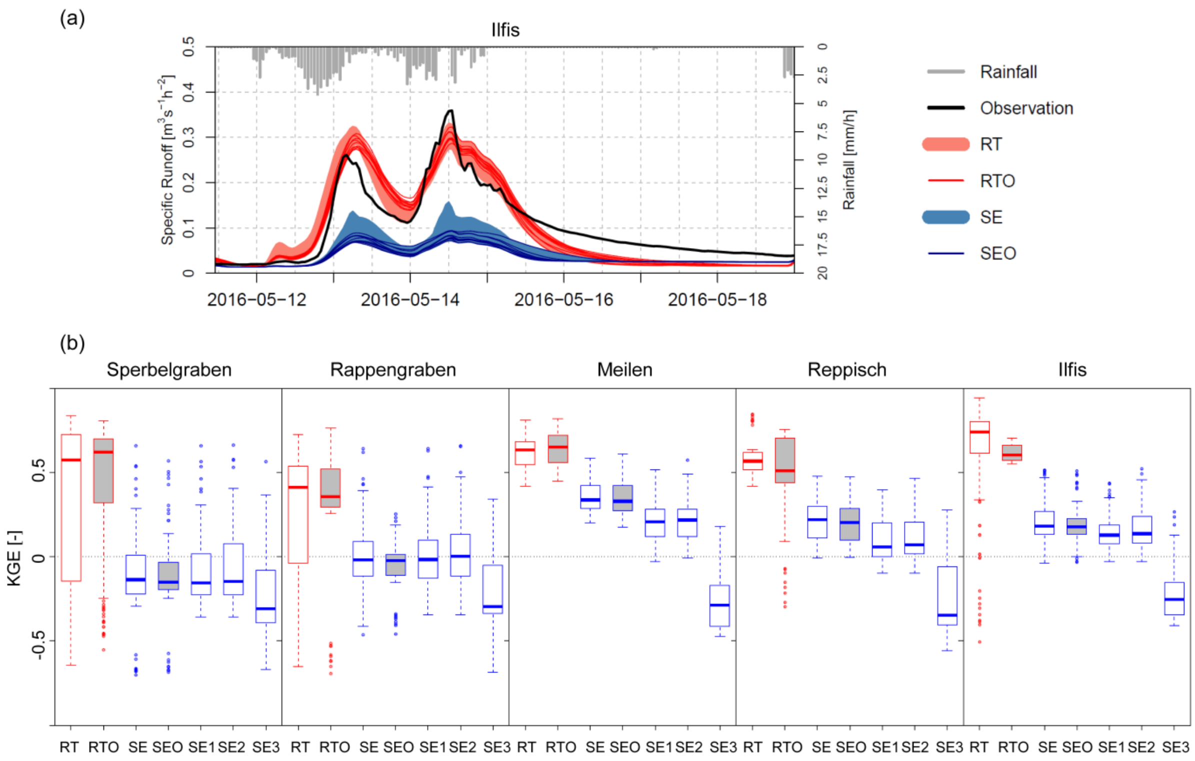


Figure II.8 (a) Simulated runoff during the rainfall event on the 28th and 29th of July 2014, obtained from the four different parameter allocation strategies. (b) Results of the simulated events on the five study catchments. Each boxplot represents the performances of ten model runs for each event. Red (blue) boxplots refer to the parameter allocation strategy based on the runoff types (sprinkling experiments). Grey (white) fill refers to parameter allocation strategies with (without) optimisation.

6.2 Comparison of runoff generation modules

When applied on the same catchments with the same precipitation input, RGM-PRO and RGM-TRD produced different results. For example, on the Sperbelgraben, Rappengraben, and Ilfis catchments during the event on 15th May 2016, both the runoff peaks and volume were well reproduced by RGM-PRO, while TRD-ParTrans and TRD-RHQ underestimated the runoff signal (Figure II.9). Only the falling limb of the hydrograph was reproduced better by RGM-TRD. Figures 10 and 11 show how RGM-PRO performed well on all the study catchments during nearly all the simulated events, and outperformed the non-calibrated TRD-1st10 in terms of highest performance and simulation uncertainty. In some instances, RGM-PRO even exceeded the performance of the calibrated RGM-TRD (represented by the upper part of the box plots of TRD-2000 in Figures II.10 and II.11).

When compared with the other regionalisation techniques, RGM-PRO performed better than TRD-RHQ and TRD-ParTrans (in Figures II.9, II.10, and II.11, configured by choosing the Sperbelgraben as the donor catchment and September 2006 as event for calibration of TRD-ParTrans). However, choosing another donor catchment and/or event for the calibration of TRD-ParTrans would have led to different results, especially for the small Rappengraben and Sperbelgraben catchments (Figure II.12).

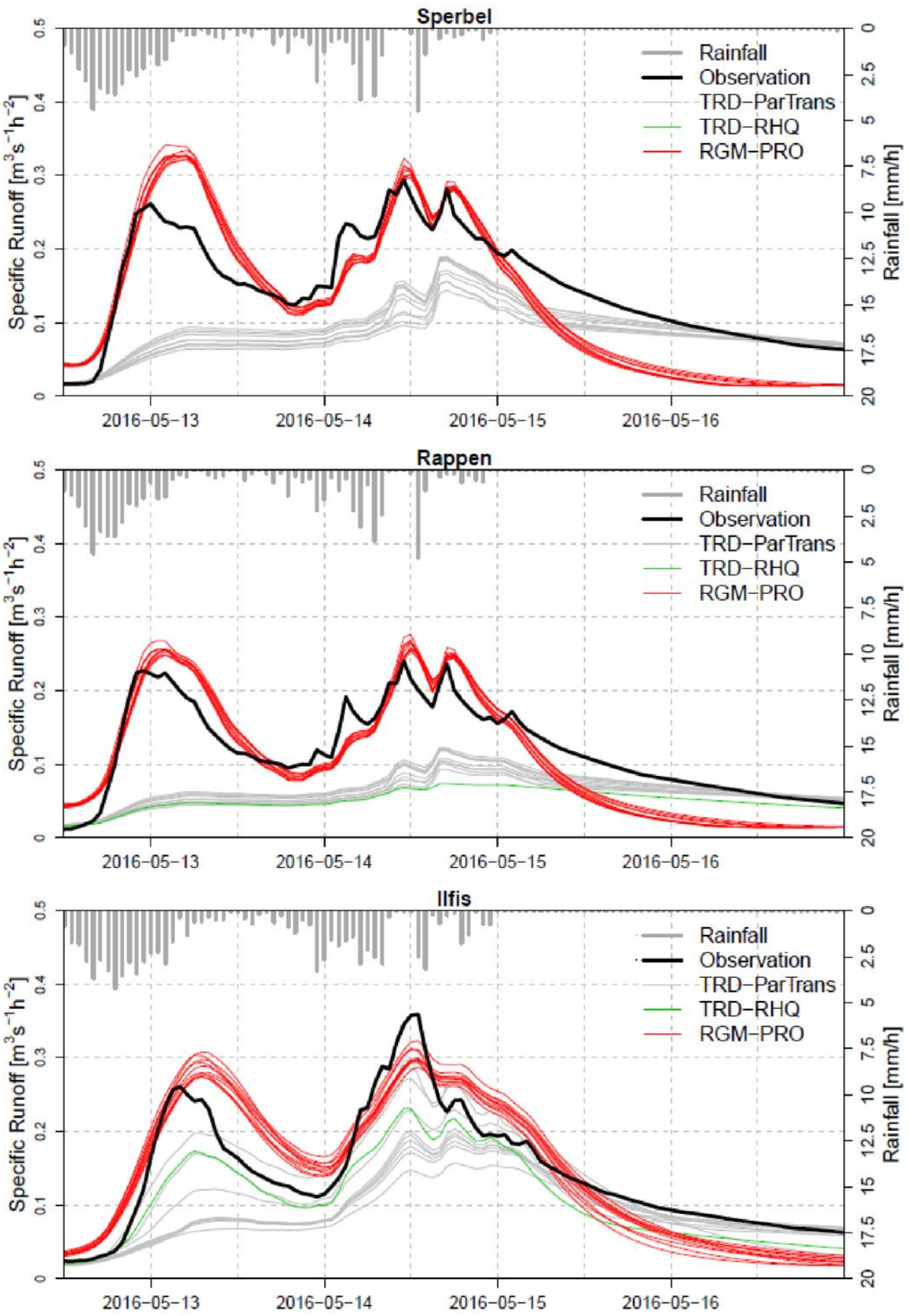


Figure II.9 Simulated runoff during the event between the 12th and 15th of May 2016, obtained from TRD-ParTrans, TRD-RHQ and RGM-PRO.

Only using the Ilfis catchment, the largest among those investigated, as the donor catchment seems to lead to the most robust calibrated parameter sets to be transferred to other areas. Using the boxplots of Figure II.12 as a proxy for uncertainty leads to the finding that RGM-PRO produced the lowest uncertainty among the model configurations.

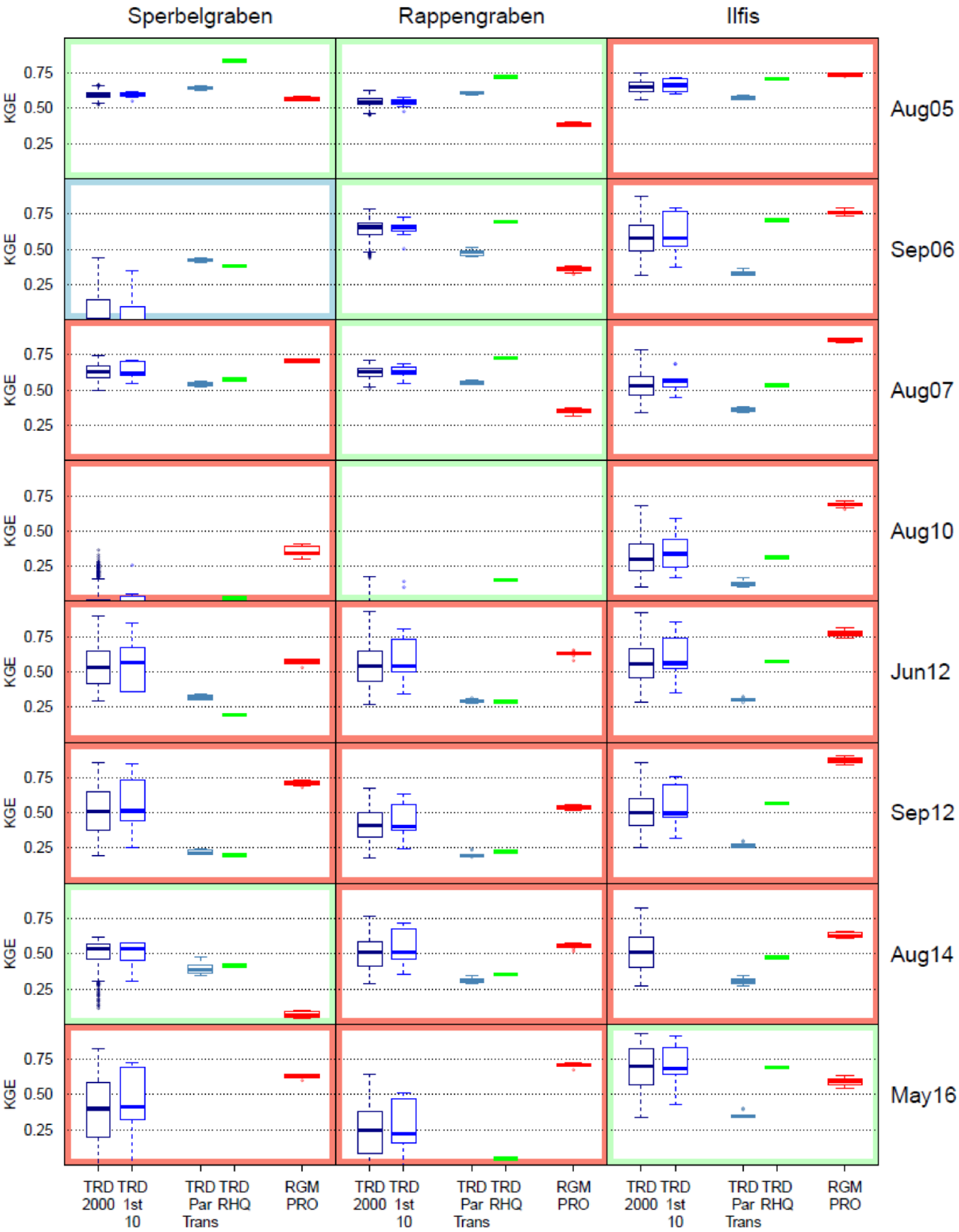


Figure II.10 Results from the eight events simulated on the Sperbelgraben, on the Rappengraben, and on the Ilfis catchment. The boxplots represent the simulation results of the different model configurations. The coloured frame indicates which model simulated the event best. TRD-ParTrans was calibrated on the Sperbelgraben during the event of September 2006.

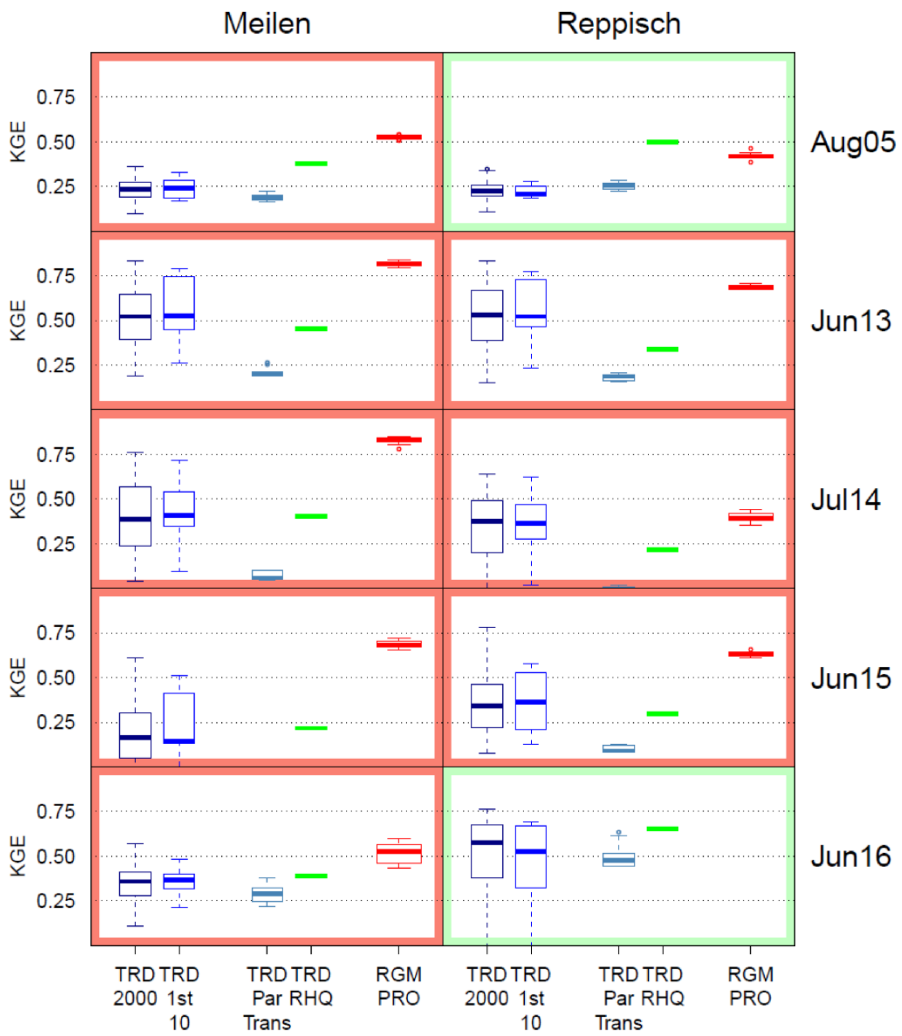


Figure II.11 Results from the five events simulated on the Meilen catchment and on the Reppisch catchment up to Birmensdorf. The boxplots represent the simulation results of the different model configurations. The coloured frame indicates which model simulated the event best. TRD-ParTrans was calibrated on the Sperbelgraben during the event of September 2006.

The results from Series Distance (Ehret and Zehe, 2011) provide further information regarding the simulation skills of the runoff generation modules. For example, on the Reppisch catchment, RGM-PRO provided the best simulation of the rising limbs in both temporal and volumetric terms, whereas both TRD-ParTrans and TRD-RHQ underestimated the amplitude of the rising and falling limbs in nearly all the simulated events (Figure II.13a). The results look similar for the other study catchments (Figure II.13b), with some exceptions. On the Ilfis catchment, for example, TRD-ParTrans generally reproduced the falling limb of the events better than TRD-RHQ and RGM-PRO did, whereas, on the Sperbelgraben, RGM-PRO did not improve the volumetric estimation of the simulated events.

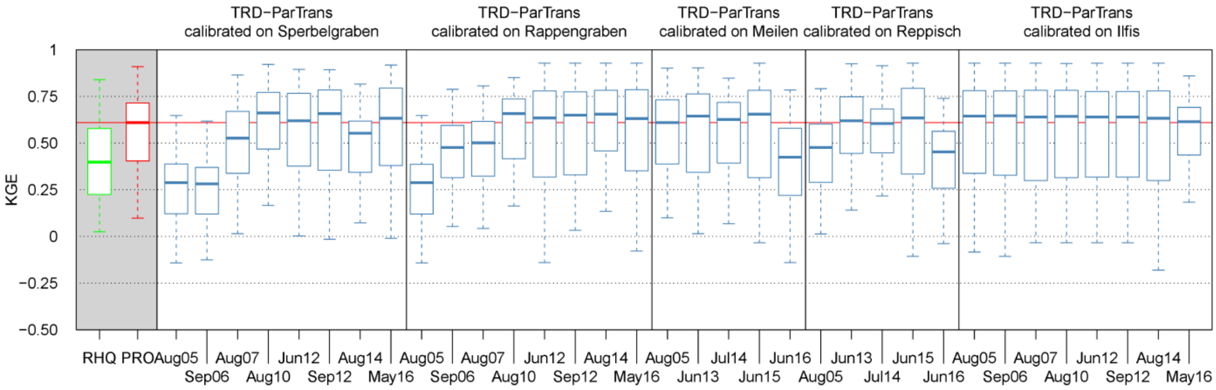
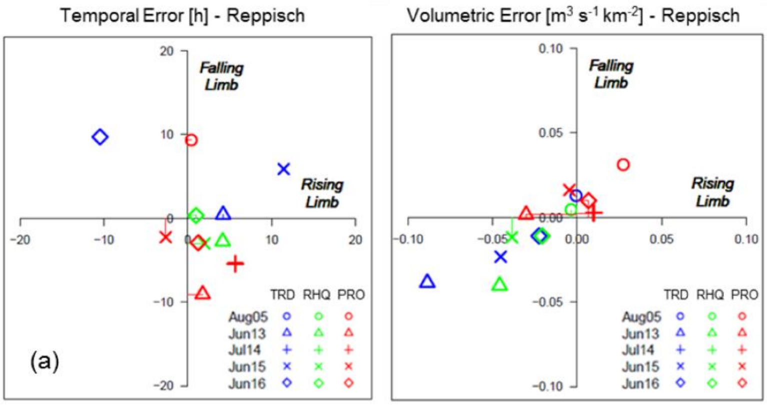


Figure II.12 Results from the leave-one-out cross validation of TRD-ParTrans. Each blue boxplot represents the simulation results obtained for all the study catchments with the 10 best parameter sets obtained by calibrating TRD-ParTrans on the catchment indicated in the title during the event indicated on the x axis. For comparison, the performances of TRD-RHQ and RGM-PRO are shown on the left, and the red horizontal line represents the median KGE reached by RGM-PRO.



Temporal shift – Rising Limb

	TRD-ParTrans	TRD-RHQ	RGM-PRO
Sperbelgraben	2	2	4
Rappengraben	0	1	7
Meilen	0	1	4
Reppisch	0	2	3
Ilfis	1	0	7

Temporal shift – Falling Limb

	TRD-ParTrans	TRD-RHQ	RGM-PRO
Sperbelgraben	1	2	4
Rappengraben	1	0	7
Meilen	0	0	5
Reppisch	2	1	2
Ilfis	4	0	4

Volumetric shift – Rising Limb

	TRD-ParTrans	TRD-RHQ	RGM-PRO
Sperbelgraben	2	3	3
Rappengraben	3	0	5
Meilen	0	0	5
Reppisch	1	1	3
Ilfis	0	1	7

Volumetric shift – Falling Limb

	TRD-ParTrans	TRD-RHQ	RGM-PRO
Sperbelgraben	2	3	2
Rappengraben	3	1	4
Meilen	0	2	3
Reppisch	0	2	3
Ilfis	5	0	3

(b)

Figure II.13 (a) Temporal and volumetric error calculated with the Series Distance (Ehret and Zehe, 2011) approach on the Reppisch catchment. Each dot corresponds to an event simulated either with TRD-ParTrans (blue), TRD-RHQ (green), or RGM-PRO (red). A vertical (horizontal) segment indicates, for each event, which model provided the best simulation of the rising (falling) limb of the hydrograph; (b) Scores calculated for all study catchments based on the Series Distance approach. For each event, the model configuration that performs best receives a point. The different background colours indicate the model configuration which performed best on the given catchment. A gradient is used in case of parity.

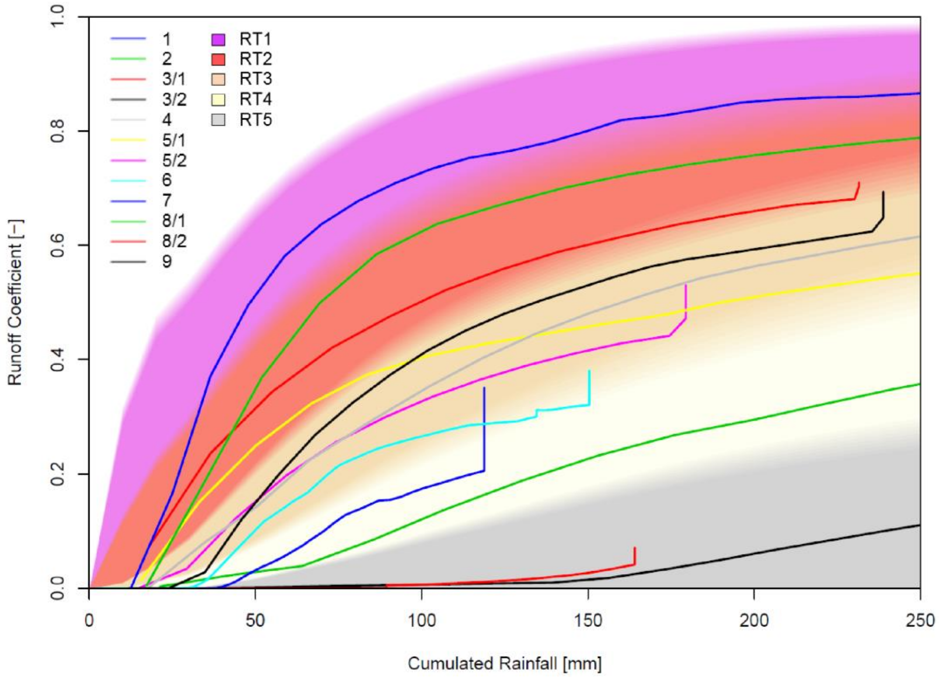


Figure II.14 Response curves of the 12 sprinkling experiments available for this study. The colours in the background refer to the expected response curves of the five runoff types according to their definition, as given in Naef et al. (2000).

7. Discussion

7.1 Parameter allocation of RGM-PRO

One of the main purposes of this study was to develop a process-oriented modelling approach based on the DRP concept, consisting of an event-based conceptual runoff generation module (RGM-PRO), and an a priori parameter allocation strategy for its application on ungauged catchments. RGM-PRO was able to simulate both overland and subsurface flow of the sprinkling experiments. Other studies reached similar results with computationally highly demanding models (Faeh et al., 1997; Steinbrich et al., 2016). In this study, we managed to reproduce the hydrographs with a conceptual, storage-based runoff generation module controlled by physically meaningful parameters, for which plausible parameters were defined a priori based on expert knowledge.

Not surprisingly, the same parameter ranges did not lead to satisfying results when applied on larger catchments, where both runoff peaks and volumes were strongly underestimated. This is mainly due to two factors. The first one is linked to the high percolation rates (in some cases even larger than 50 mm/h) inferred from the Monte Carlo simulations. Such high rates simply represent an attempt to cope with the unavoidable side leakage losses, which occurred during the measurement of both overland and subsurface flow (Scherrer et al., 2007). This error due to overfitting propagated clearly throughout the study catchment. The second factor is linked with the concept of "uniqueness of place" (Beven, 2002, 2000). As shown by Scherrer et al. (2007), the sprinkling experiments are often characterised by a unique combination of one DRP

Table II.8 DRP, subordinate process, expected and actual RT of each sprinkling experiment.

No.	Location	DRP according to Scherrer and Naef (2003)	Subordinate process according to Scherrer *et al.* (2007)	Expected RT according to Naef *et al.* (2000; Table II.3)	Actual RT (according to Figure II.14)
1	Willerzell (sink)	SOF1	SSF2	RT1	RT1
2	Bilten	SOF1	SSF1	RT1	RT2
3/1	Heitersberg	HOF1	SSF3	RT1	RT2
3/2	Heitersberg	HOF1	SSF3	RT1	RT2 - RT3
4	Therwil	SOF2	DP	RT2	RT3
5/1	Willerzell (Hillslope)	SSF2	SOF3	RT3	RT3
5/2	Willerzell (Hillslope)	SSF2	SOF3	RT3	RT3
6	Luthertal	SSF2	-	RT3	RT3-RT4
7	Schlüssberg	SSF3	-	RT4	RT4
8/1	Therwil	SOF3	DP	RT4	RT4
8/2	Therwil	SOF3	DP	RT4	RT5
9	Reiden	SSF3	DP	RT5	RT5

and one or more subordinate runoff processes, which can influence the intensity of the contribution to runoff, and, therefore, the runoff type. Figure II.14 and Table II.8 show how locations that are subject to a certain DRP according to the decision schemes of Scherrer and Naef (2003) can actually contribute to runoff in a different manner than expected. Arbitrarily choosing a single sprinkling experiment to represent a whole runoff type should therefore be avoided.

In contrast, defining a priori plausible parameter ranges, and optimising them against idealised response curves for each class of a process map, has been proved to be a promising and straightforward technique for the application of RGM-PRO at the catchment scale. A similar parameter allocation strategy is already implemented in the QAREA model family (Horat, 2000; Smoorenburg, 2015; VAW, 1994). With the approach presented in this study, however, the initialisation problems of QAREA mentioned in the introduction have been removed, and any spatially distributed soil moisture data can be used to initialise RGM-PRO.

7.2 Added value of process-based hydrological modelling

The simulation results obtained with RGM-PRO are promising, given that its performance was nearly always similar or even higher than that of the calibrated RGM-TRD. The low performances achieved in some cases (e.g. the event in August 2010 on Sperbelgraben and Rappengraben; Figure II.10) can be explained by a biased spatial distribution of the precipitation data through time, which affected the results of all the runoff generation modules. More generally, the results of our study show that, given the same uncertainties in the input data, the use of information on the spatial distribution of runoff processes allows the simulation results to be improved and the spatial representation of runoff within the catchment to be in agreement with the hydrologist's perception of the catchment functioning. This finding is in agreement with that of Nijzink et al. (2016), who improved the internal dynamics of mHMtopo by incorporating sub-grid variability based on DRPs derived with a topography-based approach (Gharari et al., 2011). In contrast, Casper et al. (2015) did not observe any improvement at the gauging site with a process-based parameterisation of LARSIM (Bremicker, 2000), and Hellebrand et al. (2011) did not find a clear improvement of their DRP-Model compared with the conceptual FLEX model (Fenicia et al., 2007). However, as already mentioned before, all these studies made use of calibration for the allocation of model parameters, which could have biased the results.

The bottom-up approach presented in this study can be seen as a successful attempt to bridge the gap between experimentalists and modellers (Seibert and McDonnell, 2002). In recent years, several attempts have been made in this direction, but in all of them the role of the modellers was larger than that of experimentalists (Euser et al., 2015; Gao et al., 2014; Gharari et al., 2014; Nijzink et al., 2016; Savenije, 2010). As a consequence, a top-down approach and strong simplified mapping approaches were mainly used for the modelling. Parameter and process relational rules were therefore used to constrain the model (e.g. FLEX-Topo; Savenije, 2010; Gharari et al., 2014). However, much more information about the reaction of a catchment to rainfall than the one provided by a topography-based landscape classification (Rennó et al., 2008) can be gained and consequently used for model building and constraining. The approach presented here, therefore, represents a framework for the use of all detailed and qualitative knowledge about processes obtained by experimentalists. This knowledge is first used during the phase of mapping the landscape, and, second, during the parameter allocation phase when plausible ranges are defined for each model parameter. The performance of a topographically-based landscape classification within a bottom-up framework was already investigated by Antonetti et al. (2016a). The advantages of using more expert knowledge on processes in a top-down approach with parameter and model constraints will be addressed in a future study.

7.3 Process-based hydrological modelling as a regionalisation approach

Mapping runoff types and using the information on their extent and distribution within an a priori parameterised runoff generation module has proven to be valuable as a regionalisation technique, given that RGM-PRO reached similar performances as TRD-RHQ and TRD-ParTrans. The process-based framework improved the simulation of the hydrographs in both temporal and volumetric terms and has advantages over the other two regionalisation techniques used in this study (i.e. TRD-ParTrans and TRD-RHQ), also in terms of robustness and transferability. As shown in Figure II.12, transferring in space and time parameters of a traditional conceptual runoff generation module is a suitable approach only above a certain catchment size (for RGM-TRD this threshold was quantified as 25 km^2 by Viviroli et al., 2009a), in agreement with expected compensation effects (i.e. error averaging) for mesoscale catchments (Blöschl, 2001). For catchments smaller than this threshold, the parameters being transferred are strongly linked with the choice of the calibration event. As a consequence, the simulation results become less robust. Spatially interpolating calibrated parameter values of a traditional conceptual runoff generation module (TRD-RHQ) is a feasible technique only for those catchments within the area where the regionalisation was designed. Applying the method to another area would imply a considerable initial effort and the regionalisation results would strongly depend on the number of calibration catchments.

Although it was applied only on five catchments located relatively close to each other, the approach presented in this paper has the potential to be transferred to any temperate catchment, provided that a process map and spatially distributed forcing are available. This transferability test, however, was beyond the scope of this study and will be object of future research.

7.4 Limitations of this study

Several limitations of our study need to be addressed in future research. For example, the sensitivity of the model results with respect to the process maps was not investigated. As shown by Antonetti et al. (2016a), simulation results are sensitive to variations in the extent and location of the runoff types within a catchment. A different definition of the representative response curves for each runoff type can also have an effect on the results. In addition, Euser et al. (2015) showed that the model structure can also affect the simulations. For example, taking into account interception could have led to different results, especially during the beginning of an event. The problems linked with the temporal shift and the excessive smoothness of the simulated hydrographs obtained with RGM-PRO could be caused by the greatly simplified representation of the runoff concentration. In fact, the storage time of the linear storage for the concentration of subsurface flow could vary among the different sub-catchments, according to their characteristics (e.g. size, drainage density, etc.). A different parameterisation of the runoff concentration could therefore have led to better results.

Although the input data used for this study (CombiPrecip product; Sideris et al., 2014) represents the state of the art of spatially distributed rainfall data available in real-time, it is most likely responsible for large uncertainties. Especially with regard to convective rainfall events, the spatial and temporal resolution of the data, as well as the typical problems linked with radar (e.g. screening effects; Germann et al., 2006), still restrict its use for hydrological applications. The same is valid for the initial conditions assimilated from PREVAH simulations, which are affected by uncertainties linked with the quality and resolution of the data used to develop the drought information platform (Zappa et al., 2014). On the Reppisch catchment, for example, the initialisation of RGM-PRO with soil moisture data with a higher resolution (200 m instead of 500 m) lead to a performance increase (not shown). For a better estimation of the effectiveness of the DRP-based concept presented in this paper, therefore, more reliable forcing data are needed.

In addition, significant uncertainties in the measured runoff data cannot be excluded (e.g. Westerberg et al., 2011). Finally, the use of further information besides runoff measurements, e.g. from environmental tracers, aerial photographs or maps of saturated areas, could have given further insights into the spatial distribution of performance of the different runoff generation modules (e.g. Güntner et al., 1999; Tetzlaff et al., 2007; Johst et al., 2008).

8. Conclusions

In this study, we introduced RGM-PRO as an event-based, process-oriented, runoff generation module based on the PREVAH hydrological modelling system, with the aim to improve simulations on ungauged catchments. RGM-PRO makes use of information on the spatial distribution of runoff types, which are defined based on expert knowledge and field work. It was fed with grid-based hourly precipitation data, while information on the soil moisture was assimilated and downscaled from continuous simulations of PREVAH.

Trying to allocate the parameter of RGM-PRO a priori based on the hydrographs of sprinkling experiments did not deliver satisfactory results, and this is attributable to the principle of uniqueness of place and side leakage losses. Allocating parameters based on generalised response curves allowed subordinate processes, heterogeneities and the process catena on the hillslope to be taken into account, and this led to better performances. Compared with the traditional, conceptual runoff generation module of PREVAH, RGM-PRO allows the spatial representation of runoff within the catchment to be more realistic without decreasing the model performance (Seibert and McDonnell, 2002). Also, simulation results of RGM-PRO were better than those obtained with other typical regionalisation techniques based on either parameter transfer or parameter regionalisation in both temporal and volumetric terms. It can therefore be concluded that including information on the spatial distribution of runoff types in a conceptual hydrological model is a feasible technique for performing hydrological simulations on ungauged catchments and for increasing model realism without resorting to the use of calibration. Future research directions should include the evaluation of different sources of uncertainties (e.g. Zappa et al., 2011; Addor et al., 2014) and the application to real-time predictions with a focus on nowcasting (e.g. Liechti et al., 2013).

Author Contributions

Manuel Antonetti and Massimiliano Zappa designed the simulations, Simon Scherrer and Peter Kienzler performed the sprinkling experiments, and Michael Margreth and Simon Scherrer produced the process maps. Manuel Antonetti prepared the manuscript with contributions from all co-authors.

Acknowledgements

We thank the Swiss Federal Office for the Environment (FOEN) for funding the PhD project of the first author. The precipitation data were provided by the Swiss Federal Office of Meteorology and Climatology MeteoSwiss, while the observed runoff series were provided by FOEN and the cantons of Zurich and Bern. We are also grateful to Jan Seibert for discussions about the methodology of the study, to Melissa Dawes for the English revision of the manuscript, and to Shervan Gharari and another anonymous reviewer for their comments on an earlier version of the manuscript.

Edited by: D. Tetzlaff

Supporting Material

See Figure S1, and Figure S2.

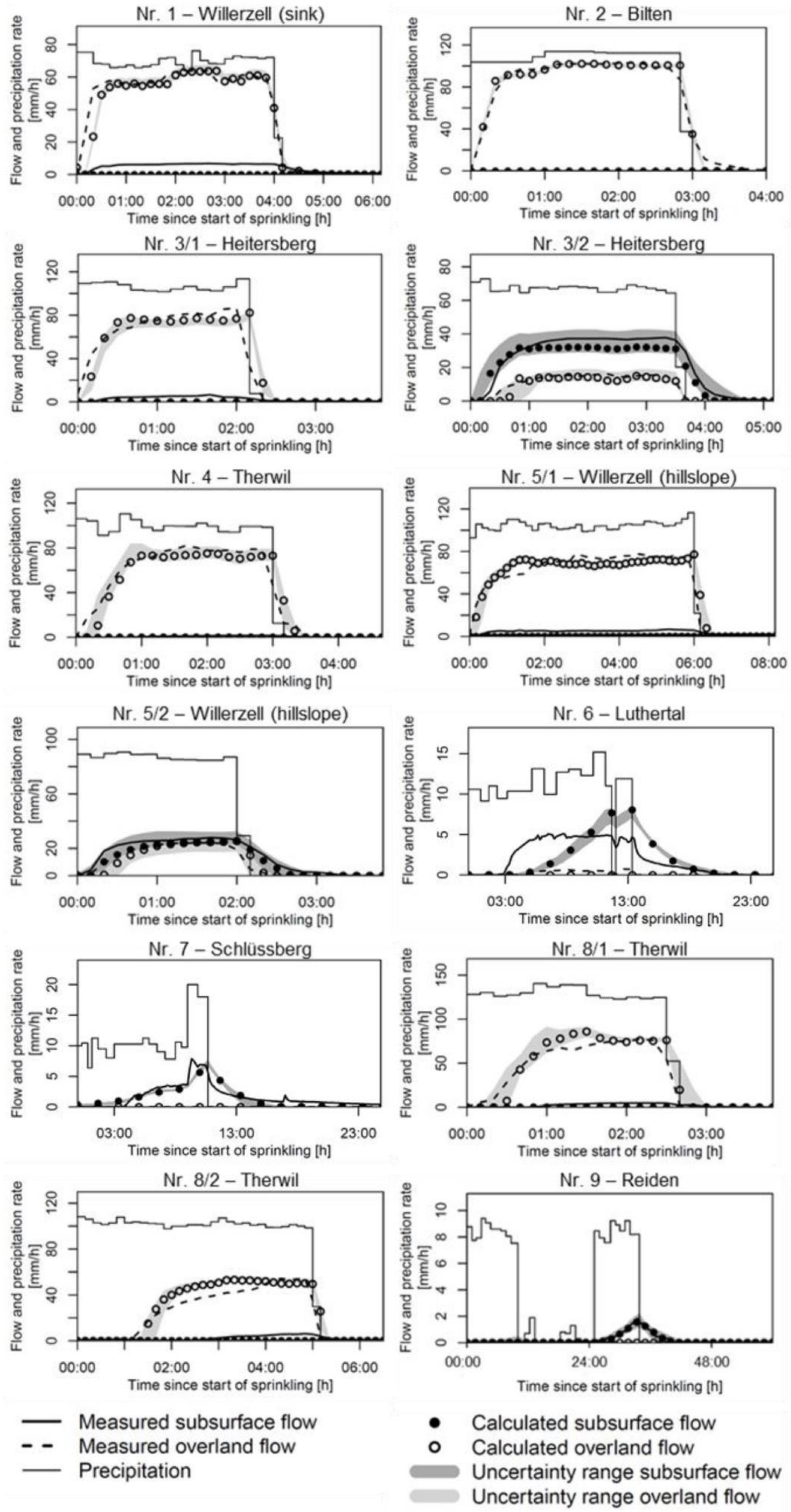


Figure S1. Hydrographs obtained from the simulation of the sprinkling experiments.

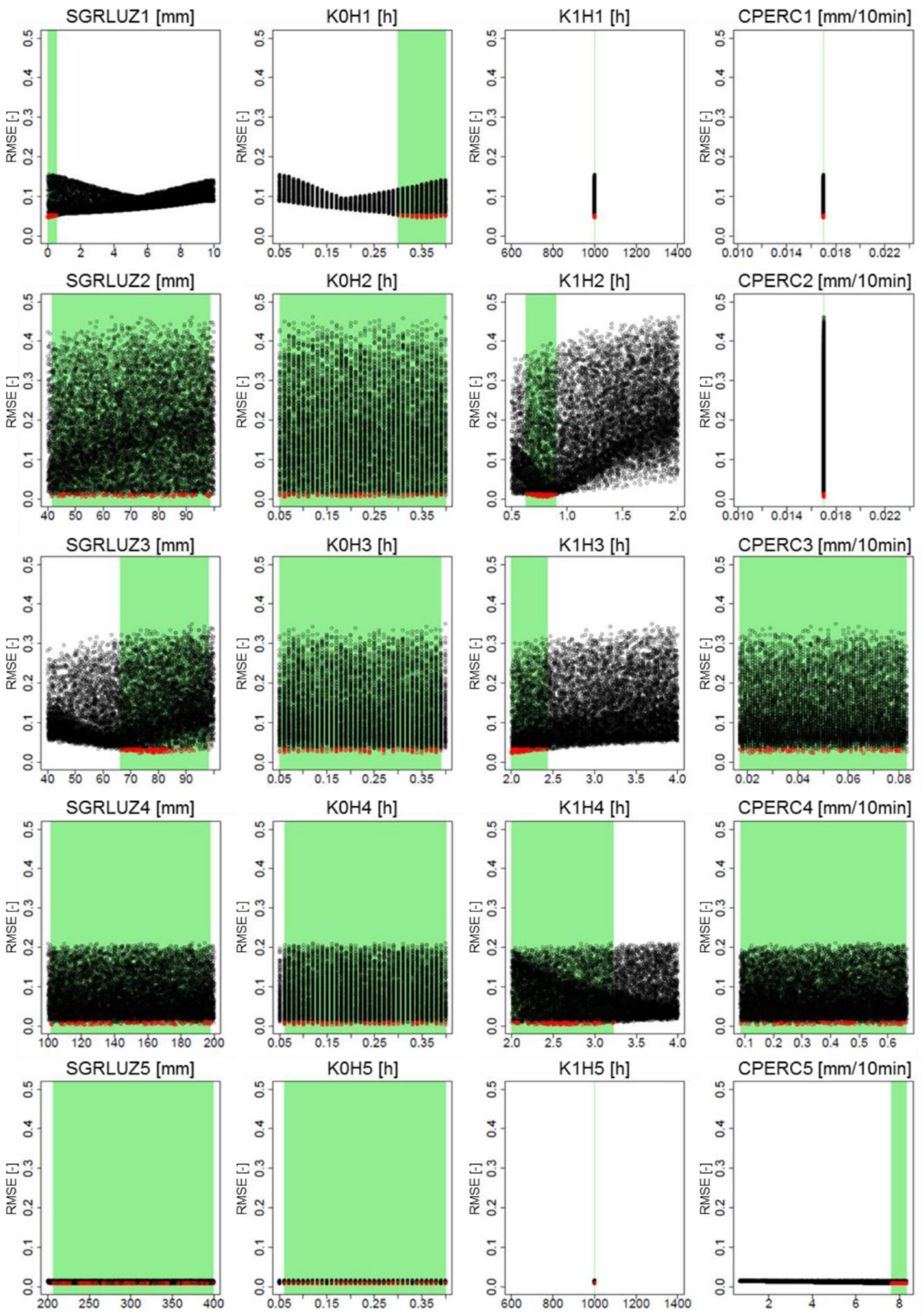


Figure S2. Dot plots obtained from the simulation of the response curves of the RTs. The red dots in the dot plots refer to the best 1% of a Monte Carlo simulation with 10,000 runs, and the green rectangles highlight the optimised parameter ranges.

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III. How can expert knowledge increase the realism of conceptual hydrological models? A case study on the Swiss Pre-Alps

In review for Hydrology and Earth System Sciences Discussion. DOI: 10.5194/hess-2017-322.

Manuel Antonetti[a,b] and Massimiliano Zappa[a]

Abstract

Both modellers and experimentalists agree that using expert knowledge can improve the realism of conceptual hydrological models. However, their use of expert knowledge differs for each step in the modelling procedure, which involves hydrologically mapping the dominant runoff processes (DRPs) occurring on a given catchment, parameterising these processes within a model, and allocating its parameters. Modellers generally use very simplified mapping approaches, applying their knowledge in constraining the model by defining parameter and process relational rules. In contrast, experimentalists usually prefer to invest all their detailed and qualitative knowledge about processes in obtaining

as realistic spatial distribution of DRPs as possible, and in defining narrow value ranges for each model parameter.

Runoff simulations are affected by equifinality and numerous other uncertainty sources, which challenge the assumption that the more expert knowledge is used, the better will be the results obtained. To test to which extent expert knowledge can improve simulation results under uncertainty, we therefore applied a total of 60 modelling chain combinations forced by five rainfall datasets of increasing accuracy to four nested catchments in the Swiss Pre-Alps. These datasets include hourly precipitation data from automatic stations interpolated with Thiessen polygons and with the Inverse Distance Weighting (IDW) method, as well as different spatial aggregations of Combiprecip, a combination between ground measurements and radar quantitative estimations of precipitation. To map the spatial distribution of the DRPs, three mapping approaches with different levels of involvement of expert knowledge were used to derive so-called process maps. Finally, both a typical modellers' top-down setup relying on parameter and process constraints, and an experimentalists' setup based on bottom-up thinking and on field expertise were implemented using a newly developed process-based runoff generation module (RGM-PRO). To quantify the uncertainty originating from forcing data, process maps, model parameterisation, and parameter allocation strategy, an analysis of variance (ANOVA) was performed.

The simulation results showed that: (i) the modelling chains based on the most complex process maps performed slightly better than those based on less expert knowledge; (ii) the bottom-up setup performed better than the top-down one when simulating short-duration events, but similarly to the top-down setup when simulating long-duration events; (iii) the differences in performance arising from the different forcing data were due to compensation effects; and (iv) the bottom-up setup can help identify uncertainty sources, but is prone to overconfidence problems, whereas the top-down setup seems to accommodate uncertainties in the input data best. Overall, modellers' and experimentalists' concept of "model realism" differ. This means that the level of detail a model should have to accurately reproduce the DRPs expected must be agreed in advance.

[a] Swiss Federal Research Institute WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland.
[b] Department of Geography, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland.

1. Introduction

Applying expert knowledge in hydrology, as in any other natural science, is crucial for linking observations and laws governing a given system, such as a catchment. It usually involves formulating and testing hypotheses about how the system functions (Savenije, 2009). At the root of this scientific reasoning, two opposing philosophies can be identified: the top-down and the bottom-up approaches. The first can be traced back to the Greek philosopher Plato (428 – 348 BC), who was trying to link general theories about the functioning of complex systems to measurable observations. A "bottom-up" approach involves extrapolating general theories from given observations, and can be attributed to Plato's student Aristotle (384 – 322 BC). These two approaches have been applied in nearly all scientific disciplines, e.g. in mathematics (Cellucci, 2013), economics (Böhringer and Rutherford, 2008) and neuroscience (Gilbert and Li, 2013), as well as hydrology. Thus one type of hydrological scientist, the experimentalist or "wet" hydrologist, tries to understand catchment functioning through extended field investigations, whereas the modeller or "dry" hydrologist tends to develop theories at the catchment scale and successively tries to validate them against measurements (Seibert and McDonnell, 2002).

Both modellers and experimentalists agree on the importance of expert knowledge for improving the realism of hydrological models, e.g. by forcing the model to reproduce the processes observed in the catchment. In recent years, several process-oriented approaches have been developed, of which the concept of dominant runoff process (DRP) is one (Blöschl, 2001). It relies on the hypothesis that, among the different runoff generation mechanisms that may occur at a given location (Hortonian overland flow HOF, saturation overland flow SOF, subsurface flow SSF, and deep percolation DP), one, the DRP, will be dominant over the others. Based on this concept, the following process-based modelling chain has been proposed (Clark et al., 2015): (i) reading the landscape, identifying and classifying the processes, (ii) developing a proper parameterisation to reflect our perceptions of the processes observed and (iii) allocating the parameter values of these parameterisations (Figure III.1).

Wet and dry hydrologists disagree, however, on how to implement their expert knowledge in each of these steps. For example, Schmocker-Fackel et al. (2007) applied the two philosophies to hydrological classifications using DRPs and claimed: "[…] These top-down approaches try to identify homogeneous landscape units. The assumption is that the hydrological response will also be homogeneous. By contrast, in bottom-up approaches, runoff formation is investigated on the plot scale and then units with the same runoff forming process are identified" (Schmocker-Fackel et al., 2007). Examples of such bottom-up mapping approaches can be found in Markart et al. (2004); Smoorenburg (2015), Scherrer AG (2006), Scherrer and Naef (2003) and Tilch et al. (2006), and of top-down mapping approaches in Gao et al. (2014), Gharari et al. (2011) and Fenicia et al. (2016).

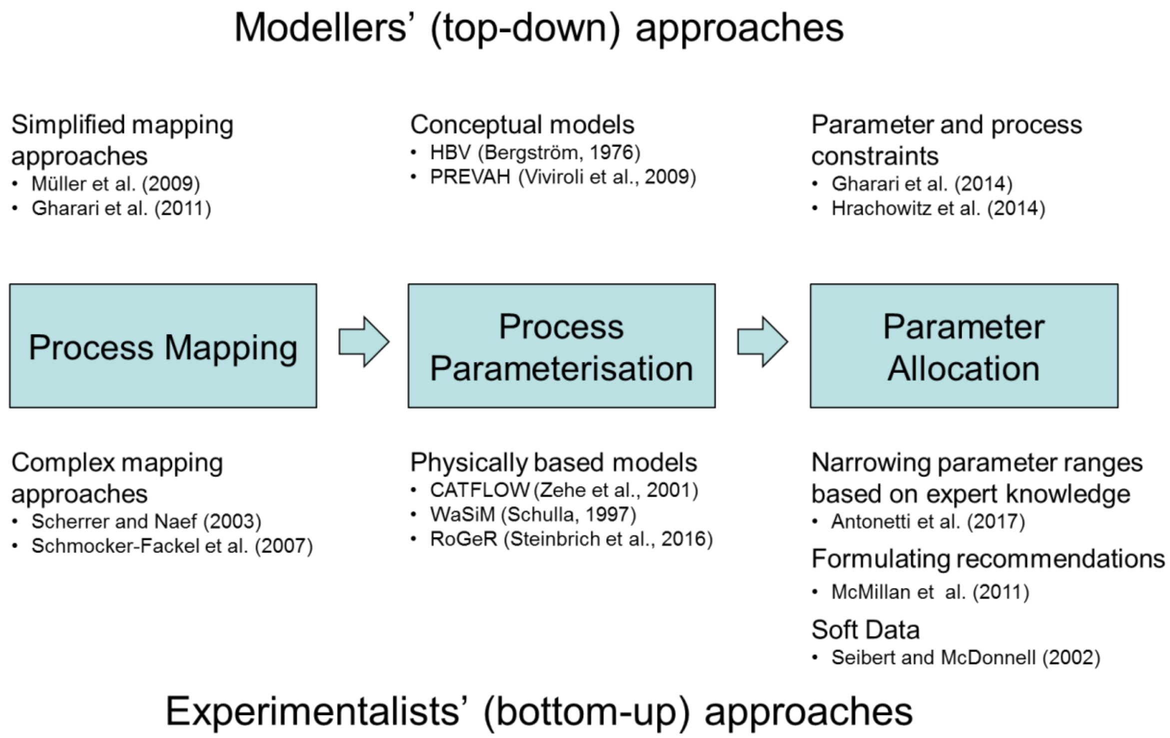

Figure III.1 The three main steps for process-based flood predictions and the differences between the bottom-up (bottom) and top-down (top) approaches.

Different interpretations of the two philosophies have been applied in hydrological modelling. For example, Hrachowitz and Clark (2017) maintain bottom-up models correspond to physically-based models, where the conservations laws on mass, momentum and energy are solved. In contrast, top-down models are conceptual models. With regard to the level of modelling detail, Nalbantis et al. (2011) linked monometric approaches, where some components are examined in detail and other ones are only roughly described, to the bottom-up philosophy and the holistic approach, when all components are modelled with the same degree of detail, to the top-down one. Sivapalan et al. (2003), in contrast, classify approaches according to the scale considered: if the modelling is performed first at the small scale of e.g. HRU, or hillslopes, and then the results are scaled up to the catchment scale, it can be defined as bottom-up, whereas lumped models developed directly at the catchment scale can be defined as top-down. The definition of Sivapalan et al. (2003) also works well with the concepts of model parameterisation and parameter allocation. For example, in a classical bottom-up exercise, parameter ranges are narrowed and/or model parameterisations are proposed based on catchments properties, expert knowledge and possibly inferences from measurements. By following a top-down approach, expert knowledge can be used instead to define relational rules between the parameters and fluxes of different landscape classes. In this way, the model is forced to behave according to the modeller's perception of the catchment functioning and the parameter space can be reduced so that no calibration is necessary (Bahremand, 2016; Gharari et al., 2014).

Both approaches have strengths and weaknesses when implementing expert knowledge in process-based hydrological modelling. Bottom-up mapping approaches are often considered to require much data (Hümann and Müller, 2013; Müller et al., 2009), whereas top-down classification approaches are considered too coarse to detect the spatial distribution of processes with enough accuracy (Antonetti et al., 2016). Top-down models and parameterisations may be too simplistic and, therefore, require calibration (e.g. Fatichi et al., 2016), whereas physically-based models may be too data demanding and not flexible enough to cope with emergent patterns at large scales (Beven, 2000).

Several attempts have been made to combine bottom-up and top-down philosophies (e.g. Klemeš, 1983; Sivapalan et al., 2003), and Hrachowitz and Clark (2017) in particular stress the need to merge forces. Similarly, Clark et al. (2017) ask: "How can we combine different perspectives on hydrologic modelling to advance the quest for physical realism?". Related questions concern the level of detail needed to reproduce the observed dynamics and pattern and how much detail the available data warrants for a meaningful parameterisation of the chosen process representation (Clark et al., 2015). Clark et al. (2016) note that the structure of the model should reflect that of the landscape. They claim that focussing on the extent to which space accounting models are limited by the available data helps testing the mapping theories and, consequently, improves how well landscape details are represented in models.

Several frameworks have been proposed for testing working hypothesis (e.g. Best et al., 2011; Fenicia et al., 2011; Kraft et al., 2011), but few addressed these questions and explicitly consider ways of implementing expert knowledge in hydrological models. For example, McMillan et al. (2011) developed a set of diagnostic tests based on field data to formulate recommendations for model building. Contextually, Clark et al. (2011) used the modelling framework FUSE (Clark et al., 2008) to allow a proper model structure to be selected based on these recommendations. However, the use of flow data to formulate the recommendations restricts the application of this method to ungauged basins (Hrachowitz et al., 2013). In addition, both the proposed recommendations and the FUSE framework are applicable exclusively at the lumped catchment scale. As a further development of FUSE, Clark et al. (2015) developed the SUMMA approach to provide a framework for both modellers and experimentalists to test alternative model discretisations, parameterisations, and numerical schemes. Nalbantis et al. (2011) compared a bottom-up and a top-down modelling approach with a focus on catchments with high human impact.

Our study is intended to explore how different ways of implementing expert knowledge in hydrological modelling can affect simulation results with a specific focus on floods. In particular, we investigated: (i) Whether the use of more expert knowledge during the mapping phase improves hydrological simulations. (ii) Under which conditions (event type, catchment characteristics) satisfying results can be reached without drawing much on expert knowledge during the mapping phase? (iii) How uncertainty in forcing data and in the initial conditions influences and/or interacts with the simulation results? (iv) How the model setup, i.e. the parameterisation approach and the parameter allocation strategy, affects the results?

To address these questions we produced so-called process maps of a mesoscale catchment in the Swiss Pre-Alps using three mapping approaches derived with different levels of involvement of experts. The effects of the differences between the process maps on runoff simulations were investigated with two different setups of the newly developed PROcess-based Runoff Generation Module (RGM-PRO; Antonetti et al., 2017), which was forced

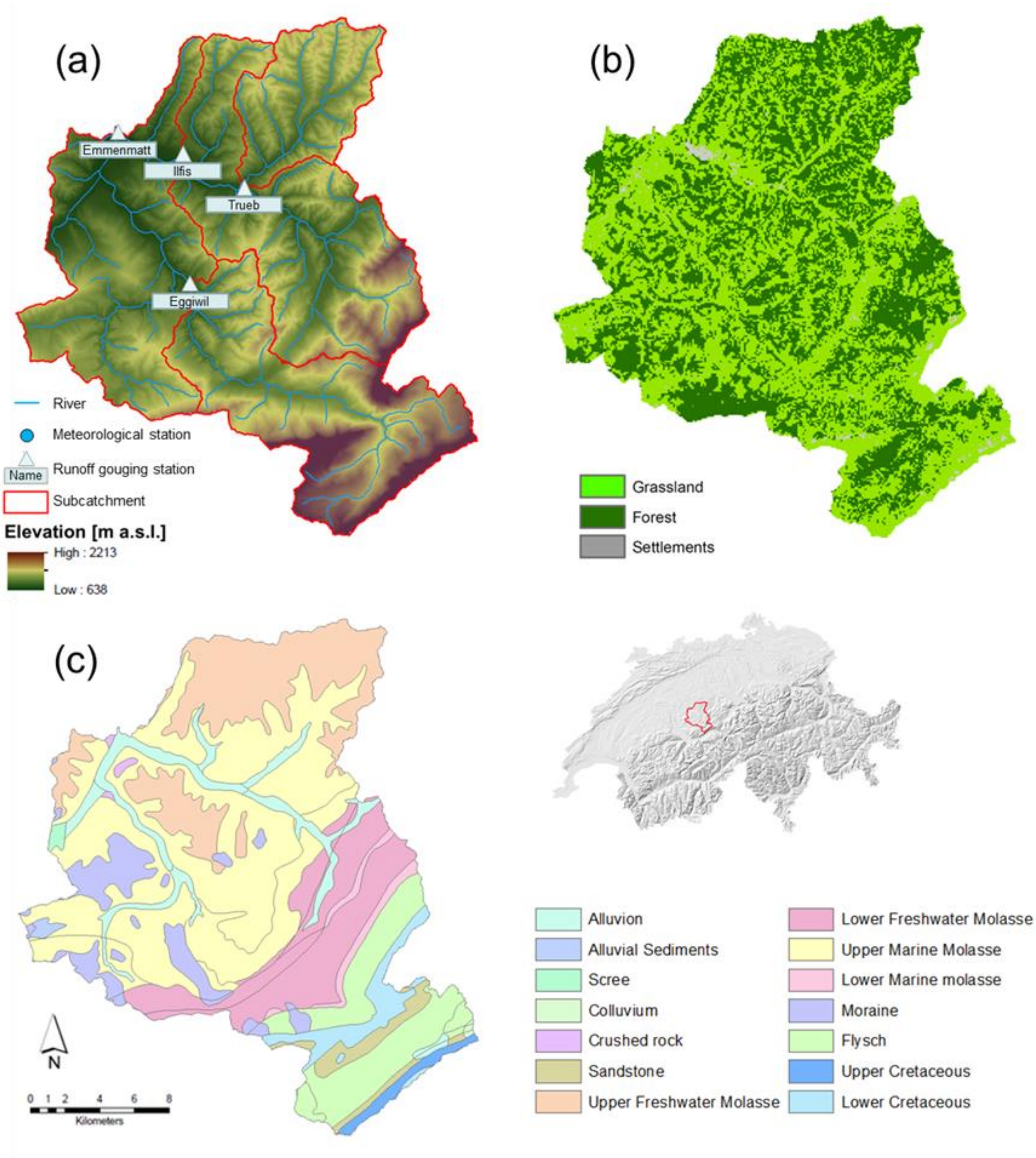

Figure III.2 Maps of the Emme catchment, Switzerland. (a) Digital terrain model (25m resolution), river network and location of the runoff gouging stations; (b) land-use map (100 m resolution); (c) geology map. Data: BFS GEOSTAT/Federal Office of Topography swisstopo (DV033492.2).

with input data of varying quality. Finally, an analysis of variance (ANOVA) was performed to quantify the uncertainty arising from forcing data, process maps, model parameterisation and parameter allocation strategy.

Table III.1 List of the hydrological classifications used in this study, the data they require, the number of output classes used, and, in brackets, the number of output classes with the original approach. Adapted from Antonetti et al. (2016)

Abbr.	Authors	Topography	Land use	Geology	Soil maps	Extensive field investigations	Number of output classes
GH11	Gharari et al. (2011)	X					3
MU09	Müller et al. (2009)	X	X	X			5(9)
SF07	Schmocker-Fackel et al. (2007)	X	X	X	X	X	5(12)

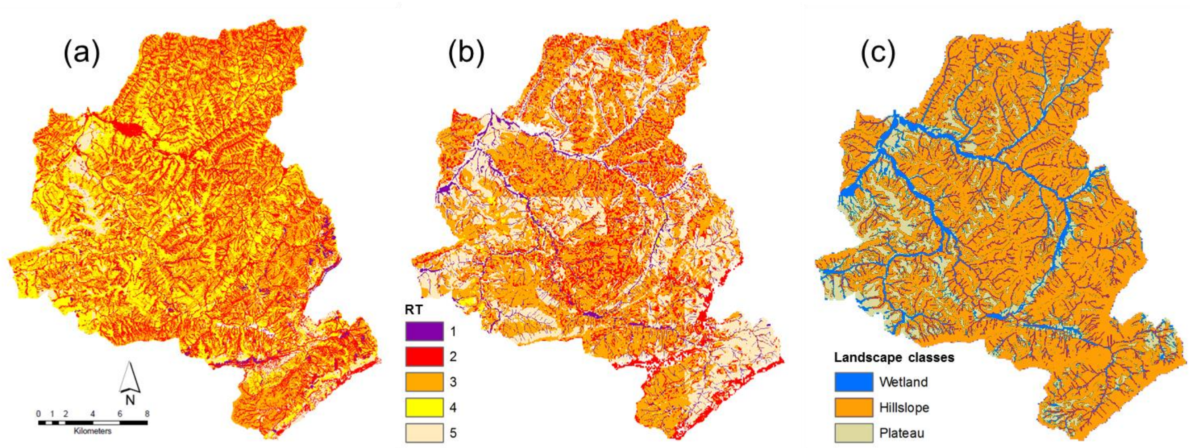

Figure III.3 Process maps for the Emme catchment map according to (a) Schmocker-Fackel et al. (2007), (b) Müller et al. (2009), and (c) Gharari et al. (2011). RT = runoff type.

2. Methods and data

2.1 Study area and process maps

We performed simulations on the Emme catchment up to Emmenmatt (445 km^2), which is located in the Pre-Alps mainly in Canton Bern and, on the eastern side, in Canton Lucern (Figure III.2). Its elevation ranges from 638 to 2213 m a.s.l.. About half of the catchment (52%) is covered by meadows, and the remaining part by forests (44%) or settlements (4%). The upper part of the catchment is characterised by Flysch and Cretaceous, whereas Freshwater and Marine Molasse and, to a lesser extent, Moraine dominate the lower part of the basin. Three additional runoff gauging stations can be found in Eggiwil (Emme catchment, 125 km^2), Langnau i.E. (Ilfis catchment, 184 km^2) and Trubschachen (Trueb catchment, 55 km^2), and their measurements were used for this study to evaluate the performance of the models.

The study catchments were mapped according to three approaches with different levels of expert involvement and differing in terms of the data and the time required for mapping (Table III.1; Figure III.3). The simplest mapping approach includes solely topographical information and distinguishes three landscape classes, i.e. wetland, hillslope

Table III.2 Reclassification of DRPs in runoff types according to their contribution to runoff (HOF = Hortonian Overland Flow; SOF = Saturation Overland Flow; SSF = Subsurface Flow; DP = Deep percolation). 1 represents an almost immediate reaction, 2 a slightly delayed one and 3 a greatly delayed one. Adapted from Naef et al. (2000).

Runoff type	DRP	Runoff intensity
RT 1	HOF1/2, SOF1	Fast
RT 2	SOF2, SSF1	Slightly delayed
RT 3	SSF2	Delayed
RT 4	SOF3, SSF3	Greatly delayed
RT 5	DP	Not contributing

and plateau, by combining the Height Above the Nearest Drainage (HAND) descriptor (Rennó et al., 2008) and slope (Gharari et al., 2011). These classes are supposed to be a proxy for saturation overland flow (SOF), subsurface flow (SSF), and deep percolation (DP). The expert knowledge involved in this mapping approach is restricted to verifying the classification criteria. We refer to the process maps derived with the Gharari et al.'s (2011) approach as GH11 maps. Müller et al. (2009) developed classification criteria that take into account the topography (slope), land use and permeability of the geological substratum where again expert knowledge is only required for verification phase. This results in nine output classes, where, beside the DRP, information on the process intensity is provided with a number from "1" (almost immediate reaction) to "3" (strongly delayed reaction). As the classification was developed by optimising the classification criteria against a reference map, the method can be also seen as top-down. The resulting process maps are referred to as MU09 maps.

Such simplistic, top-down mapping approaches have been criticised by experimentalists for finding no direct relationships between the runoff coefficient and slope (e.g. Scherrer, 1997). The third mapping approach we used is based on the experimentalist approach introduced by Schmocker-Fackel et al. (2007) and Margreth (2010), which has already been used in, for instance, Antonetti et al. (2016) and Antonetti et al. (2017). Basically, the approach consists of the following steps. (1) All the available information about a given catchment, including its topography, land use, vegetation, soil, geology, and hydrogeology, is collected and the classification algorithm adapted accordingly. (2) Small test areas are identified and manually mapped according to Scherrer AG (2006). (3) The parameter values of the algorithm are identified by comparing the automatically derived map with that derived manually on the test area. (4) Locations where estimations are not straightforward are verified with a field survey and, where necessary, adjustments are carried out. (5) Step (4) is reiterated until the process map is considered to be consistent with reality. Expert knowledge plays a crucial role in this bottom-up method, as all the experimentalists' detailed and qualitative knowledge about processes can be drawn on in the mapping. To reduce the number of resulting classes, the DRPs of MU09 maps and SF07map were reclassified into five different runoff types (RTs) according to the intensity of the contribution to runoff (Table III.2).

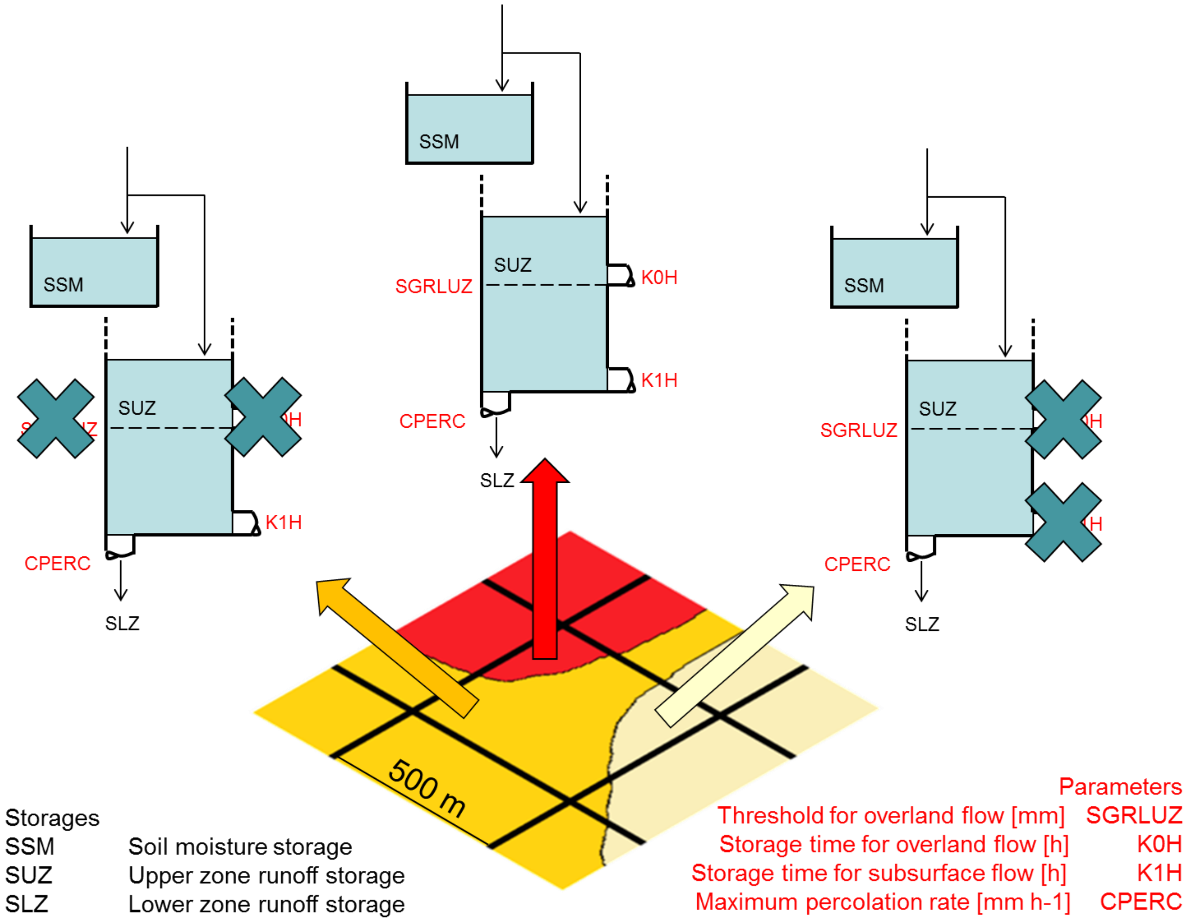

Figure III.4 Schematic representation of the spatial discretisation and structure of RGM-PRO. For each class of a given process map, a specific storage system can be defined.

2.2 The Runoff Generation Module RGM-PRO

The implementation of a physically-based hydrological model was beyond the scope of this study even though the goal was to combine bottom-up and top-down approaches at each step in the modelling chain. This could be seen to go against the definition of bottom-up model favoured by Hrachowitz and Clark (2017) and others, who associate it with physically-based. The concepts "bottom-up" and "top-down" can, however, be interpreted differently even if applied to the same topic and some researchers recommend using a semi-distributed conceptual model to accommodate the features of a catchment efficiently (Savenije and Hrachowitz, 2017). To perform the hydrological simulations for this study the newly developed conceptual PROcess-based Runoff Generation Module (RGM-PRO) was therefore used (Antonetti et al., 2017).

RGM-PRO has a grid based discretisation and was applied with a grid size of 500 m. It is able to take into account the sub-grid variability of the output classes of the process maps (Figure III.4). The model is structured so that a specific combination of storages can be defined for each output class of a given hydrological classification, with one storage system for the plant-available soil moisture (SSM), one for the runoff generation (SUZ) controlled by four parameters, and a third for groundwater (SLZ; cf. Gurtz et al., 2003; Viviroli et al., 2009b). The separation of rainfall between the storage of plant-available soil moisture and the runoff generation module is controlled by a non-linearity parameter (BETA) fixed here at a value of 3 (Viviroli et al., 2009a). In SUZ, the storage times for overland flow (K0H) and subsurface flow (K1H) regulate the generation of the runoff. A threshold (SGRLUZ) determines the separation between overland and subsurface flow, whereas a maximum percolation rate (CPERC) controls the percolation to the groundwater storage. This is divided into one quick-leaking and two slow-leaking storages controlled by three parameters (SLZ1MAX, CG1H, and K2H). For a more detailed description of the groundwater storage system, see Viviroli et al. (2009b) and Schwarze et al. (1999). This basic structure can then be adapted according to the features of the output classes of a given hydrological classification.

2.2.1 Model initialisation

The initial conditions can significantly affect simulation results (Liechti et al., 2013). For example, in a study about the uncertainties involved in operational flood forecasting chains in an alpine Swiss catchment, Zappa et al. (2011) found that uncertainty in initial conditions lasts for the first 48 hours, but is almost negligible compared with the uncertainty originating from meteorological data. To investigate to which extent the initial wetness conditions of a catchment affect simulation results with the event-based RGM-PRO, information on the plant-available soil moisture is assimilated from quasi-operational grid-based simulations of PREVAH with a resolution of 500 m (Zappa et al., 2014). At the beginning of the simulations, therefore, the soil moisture value simulated with the PREVAH hydrological system was assigned to each output class of the corresponding cell. Alternatively, as the spatial variability of the soil moisture is higher than the model resolution (500 m), the hydrological downscaling technique described in Blöschl et al. (2009) and used in Antonetti et al. (2017) was implemented. The technique relies on three assumptions: (i) the soil moisture pattern at the smaller scale is time invariant, which allows the process maps to be used as fingerprint; (ii) the spatial variance of the soil moisture at the smaller scale is linked with the one at the larger scale by a scaling theory taken from literature (Blöschl et al., 2009); and (iii) the soil moisture is mass conserving. After the soil moisture was downscaled to a resolution of 25 m, it was successively re-aggregated to obtain an average value for each output class and for each grid cell. Although no expert knowledge is directly involved in this step, the influence of the downscaling technique on the results was still investigated.

2.3 Parameterisation and parameter allocation strategies

Our investigation focussed on floods, where the main processes to be parameterised are the runoff generation within the catchment, the runoff concentration to the drainage net and runoff routing in the stream channel. According to Sivapalan et al.'s (2003) definition, in a bottom-up modelling experiment these three steps are generally parameterised in an explicit manner in the model (Figure III.5). For example, runoff concentration can be taken into account by using a lag function, a linear storage or a combination of them

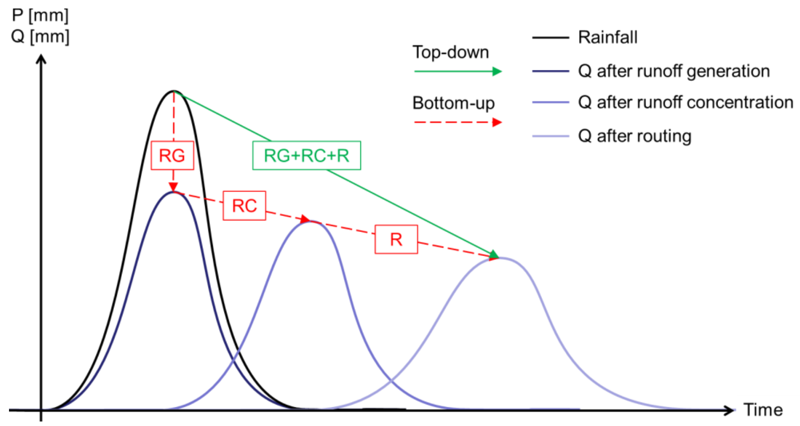

Figure III.5 Representation of runoff generation (RG), runoff concentration (RC) and routing (R) in the bottom-up (red) and in the top-down (green) setups. Adapted from Krebs et al. (2000).

(e.g. Nash, 1957). In a similar way, runoff routing can be considered with a hydraulic approach (for a review, see Heatherman, 2008) or a simpler method such as linear storage in the so-called hydrological approach. Conversely, in a top-down configuration, runoff generation, concentration and routing do not necessarily have to be treated separately (Fig. 5). In both the bottom-up and top-down parameterisations, a consistent parameter allocation strategy was implemented as described in the following sections.

2.3.1 Bottom-up setup: a priori definition of parameter ranges

For the bottom-up setup, RGM-PRO was configured as in Antonetti et al. (2017). The main catchment was first subdivided into several sub-catchments up to 2 km^2 in area. The runoff concentration to the outlet of each sub-catchment was therefore explicitly modelled for both overland and subsurface flow. For overland flow, the flow times were calculated using a semi-hydraulic approach (Schulla, 1997), and for subsurface flow a linear storage with one single parameter (GS1H, a storage time) was used. The flow times for the runoff routing in the channel were calculated with a Strickler coefficient of 30 m$^{1/3}$ s^{-1} (Schulla, 1997).

For the allocation of parameters, plausible value ranges were defined a priori for each parameter of RGM-PRO based on the results of sprinkling experiments, on physical properties of soils, and on expert knowledge (Table III.3, see Antonetti et al., 2017). By optimising these initial ranges against generalised response curves for each runoff type, they were then further narrowed before being applied to the catchments. As the response curves refer exclusively to the total runoff, the parameter ranges were defined in a manner that allows overland flow and subsurface flow to be partitioned in different ways, provided that the total contribution to runoff reflects that of the corresponding response curve. The number of output classes of the process map by Gharari et al. (2011) differs from that of the process maps used in Antonetti et al. (2017) for the identification of plausible parameter ranges. However, by comparing the landscape classes and runoff types on two catchments on the Swiss Plateau using similarity measures, Antonetti et al. (2016) found out that the most similar pairs were wetland-RT1, hillslope-RT3, and plateau-RT5. The same initial ranges of these runoff types were therefore assigned to the corresponding landscape class accordingly.

Table III.3 Parameter ranges for the top-down and bottom-up model configurations.

Bottom-up		Runoff type					Landscape class		
		RT1	RT 2	RT 3	RT 4	RT 5	Wetland	Hillslope	Plateau
SGRLUZ	[mm]	0-40	40-100	40-100	100-200	200-400	0-40	40-100	200-400
K0H	[h]	0.05-0.4	0.05-0.4	0.05-0.4	0.05-0.4	0.05-0.4	0.05-0.4	0.05-0.4	0.05-0.4
K1H	[h]	1000	0.5-2	2-4	2-4	1000	1000	2-4	1000
CPERC	[mm h^{-1}]	0.1	0.1	0.1-0.5	0.5-5	5-50	0.1	0.1-0.5	5-50
GS1H	[h]					1-3			
Top-down		**Runoff type**					**Landscape class**		
		RT 1	RT 2	RT 3	RT 4	RT 5	Wetland	Hillslope	Plateau
SGRLUZ	[mm]	0-10	5-20	15-50	20-100	80-200	0-30	20-40	30-50
K0H	[h]	1-30	1-30	1-30	1-30	1-30	1-30	1-30	1-30
K1H	[h]	10-60	10-60	10-60	10-60	10-60	10-60	10-60	10-60
CPERC	[mm h^{-1}]	0.04-0.2	0.04-0.2	0.04-0.2	0.04-0.2	0.04-0.2	0.04-0.2	0.04-0.2	0.04-0.2

2.3.2 Top-down setup: parameter and process constraints

The storage constants for overland flow (K0H) and subsurface flow (K1H) in a top-down approach are expected to represent all three steps of the runoff process described above, i.e. runoff generation, concentration and routing, as in the PREVAH hydrological model (Viviroli et al., 2009a). For the parameter allocation, the initial ranges were defined for each parameter and each output class of the hydrological classification according to Viviroli et al. (2009b), who identified a range of suitable values for each parameter of PREVAH for flood predictions in ungauged mesoscale Swiss catchments (Table III.3).

In addition, the model parameter were forced to respect the following constraints:

$$\begin{array}{l}\vartheta_{RT1} < \vartheta_{RT2} < \vartheta_{RT3} < \vartheta_{RT5} < \vartheta_{RT5} \\ \vartheta_{WETLAND} < \vartheta_{HILLSLOPE} < \vartheta_{PLATEAU}\end{array} \qquad \vartheta = \text{SGRLUZ, K0H, K1H, CPERC.} \qquad (1)$$

For those parameters of RGM-PRO physically similar to those of FLEX-Topo, the same constraints as those imposed by Gharari et al. (2014) were defined for the three landscape classes wetland, hillslope, and plateau. For example, the threshold for the activation of overland flow SGRLUZ was forced to be lower for wetlands, which have a lower storage capacity than the two other landscape classes of the GH11 maps. Similarly, the storage times for both overland and subsurface flow were set to be higher for plateaus than for hillslopes, which were in turn set higher than those for wetlands. The only exception was the storage time for the subsurface flow K1H for wetland (SOF) and plateau (DP). This was set at 1000 h as no subsurface flow was expected there according to hydrologists' understanding of SOF and DP. Similarly, the maximum percolation rate CPERC was forced to be higher for plateaus than for hillslope and wetlands. As the overland flow is expected to be faster than subsurface flow independent of the landscape class, the constraint between the two storage times were defined as follows:

$$K0H_i < K1H_i \qquad i = RT1-5, WETLAND, HILLSLOPE, PLATEAU \qquad (2)$$

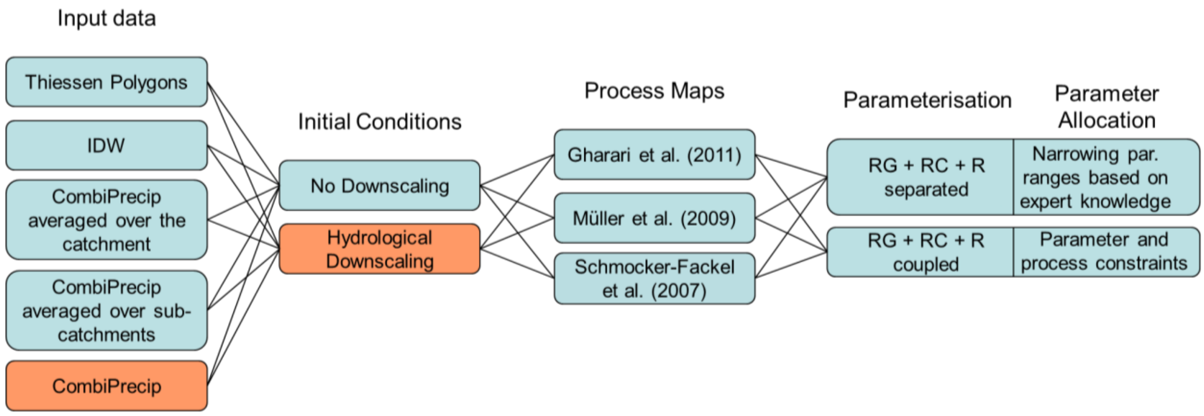

Figure III.6 Diagram of the modelling chain combination performed for this study. The components with an orange background form the benchmark modelling chain. IDW = Inverse Distance Weighting; RG = runoff generation; RC = runoff concentration; R = routing.

Following the same reasoning, parameter constraints were defined for the five runoff classes of the SF07 and MU09 maps (Eq. 1-2). One process constraint in addition to the parameter constraints was defined, namely that the specific peak runoff ($qmax$) should be higher for faster runoff types (Eq. 3):

$$qmax_{RT1} > qmax_{RT2} > qmax_{RT3} > qmax_{RT4} > qmax_{RT5} \qquad (3)$$

or for landscape classes (Eq. 4):

$$qmax_{WETLAND} > qmax_{HILLSLOPE} > qmax_{PLATEAU} \qquad (4)$$

Randomly selected parameter sets satisfying the parameter constraints were used to run the modelling chain combinations in the top-down setup. After the simulations, the runs also satisfying the process constraint were then used for the model evaluation, whereas the other runs were discarded (Gharari et al., 2014).

2.4 Experimental design

To address the research questions, a total of 60 modelling chain combinations were designed (Figure III.6). To investigate the interaction between expert knowledge and quality of forcing data, meteorological data with increasing levels of accuracy were used. Precipitation data from five automatic stations in or close to the basin with a hourly resolution were interpolated based on Thiessen polygons (Thiessen, 1911) and following an Inverse Distance Weighting (IDW) method (Isaaks and Srivastava, 1989) with the power parameter p set equal to 2. In addition, the Combiprecip product (Sideris et al., 2014), a combination of ground measurements and radar quantitative estimations of precipitation, was used. To gradually increase the degree of realism, different spatial aggregations of Combiprecip were introduced. First, for each time step, the average precipitation intensity was distributed all over the main basin. In the next configuration, the average precipitation intensity was calculated for and assigned to the corresponding subcatchment. Finally, the Combiprecip data were used directly as they were delivered by MeteoSwiss. A total of six events were simulated with each modelling chain combination (Table III.4). According to the flood type classification of Sikorska et al. (2015), three of them can be classified as short-duration events, and the remaining three as long-duration events. The event in August 2005 was also considered in this study even though

Table III.4 Start and end of the simulated events. IDW = Inverse Distance Weighting, THY = Thiessen Polygons.

Abbreviation	Simulation start	Simulation end	Event type according to Sikorska et al. (2015)	Specific peak runoff measured at Emmenmatt [$m^3 s^{-1} km^{-2}$]	No. of stations available for IDW and THI
Aug10	29.07.2010	31.07.2010	Short-duration	0.48	2
Sep12	11.09.2012	13.09.2012	Short-duration	0.40	5
Aug14	11.08.2014	12.08.2014	Short-duration	0.61	5
Aug05	19.08.2005	24.08.2005	Long-duration	1.08	-
Jun12	07.06.2012	15.06.2012	Long-duration	0.19	5
May16	11.05.2016	15.05.2016	Long-duration	0.34	5

no data from the automatic meteorological stations were available, as it was by far the largest flood event to have taken place in the last decades in Switzerland (Hegg et al., 2008).

At the beginning of each simulation, for each grid cell, the spatially distributed soil moisture data from PREVAH simulations were either directly assigned to each output class, i.e. runoff type or landscape class, or first downscaled (section 2.2.1) and successively re-aggregated to obtain an averaged value for each output class from the process map. The three mapping approaches of increasing complexity described in section 2.1 were used to map the spatial distribution of the DRP areas. Finally, the two parameterisations of section 2.3 were applied, each with its own parameter allocation strategy. For the modelling chain combinations based on the bottom-up setup, 10 different combinations of parameter values were randomly selected within the ranges defined a priori (section 2.3.1) to gain insights into the parameter uncertainty. For each modelling chain based on the top-down setup, a Monte Carlo simulation with 100 runs was performed for the same reason. To make comparison fairer, however, only the first ten combinations satisfying the process constraint were considered. For both setups, the value distribution within each range was assumed to be uniform.

The modelling chain combinations forced with the best quality and most realistic data, i.e. those driven with Combiprecip data and hydrological downscaled soil moisture data, were treated as the benchmark modelling chains.

Simulations were evaluated with the Kling Gupta Efficiency (KGE; Gupta et al., 2009):

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2} \qquad (5)$$

This allows not only the correlation between the simulated and measured runoff (r) to be taken into account, but also the ratio between the standard deviation of the simulated runoff and that of the measured runoff (s), and the ratio of the mean simulated to the mean observed discharge β. Furthermore, to quantify any potential overconfidence problems with the model setups, two factors were calculated, the P-factor and the R-factor (Abbaspour et al., 2009). The P-factor is the fraction of the measured runoff enveloped by the uncertainty band originating from the different runs of the Monte Carlo simulations, whereas the R-factor is the average width of the uncertainty band divided by the standard deviation of the measured runoff. Ideally, the P-factor is equal to 1, meaning that the observed hydrograph is bracketed by the model parameter uncertainty, whereas the R-factor tends to be zero, i.e. the simulation has the smallest uncertainty band.

Finally, to obtain insights into which uncertainty source contributes most to the total predictive uncertainty, an analysis of variance (ANOVA) was carried out. Compared to other sensitivity analysis methods, ANOVA was found to yield the most robust results without much computational efforts (Tang et al., 2007). ANOVA is based on the assumption that the uncertainty of an environmental system can be explained by the output variance generated by different effects, and has already been used to assess uncertainty, for instance, in climate impact projections (Addor et al., 2014; Bosshard et al., 2013; Köplin et al., 2013) and agro-hydrological applications (Moreau et al., 2013). ANOVA helps to clarify the question of how much of the available expert knowledge is worth feeding into a hydrological classification, given the unavoidable uncertainty linked with the input data. Assuming that all the chain components have an effect on the variability of the simulation performance ΔKGE, the following effect model was used:

$$\Delta KGE = \overline{KGE} + ID_a + IC_b + PM_c + PP_d + I_{abcd} + \varepsilon_{abcd} \quad (6)$$

Where $\overline{KGE}$ represents the mean performance of the modelling chain combinations, ID_a is the main effect of the input data (a = THI, IDW, CPC.mean, CPC.mean.subc, CPC), IC_b is the main effect related to the initial conditions (b = with and without hydrological downscaling), PM_c is related to the process maps with increasing amount of expert knowledge (c = GH11, MU09, and SF07), and PP_d to the parameterisation and parameter allocation approaches (d = bottom-up, and top-down). I_{abcd} represents the interactions between the main factors and ε_{abcd} the residual error. Each effect is checked for its representativeness and only those with a p-value lower than 0.05 are taken into account (Chambers et al., 1992)

3. Results

Using the benchmark modelling chain (i.e. Combiprecip and downscaled initial soil moisture data) and varying the process maps produced different results on the catchments investigated, depending on the model setup (i.e. parameterisation and parameter allocation strategy) used. For example, in the Emme catchment up to Emmenmatt during the rainfall events of August 2005 (Figure III.7a) and September 2012 (Figure III.7b), the modelling chain based on the SF07 map simulated best the runoff peaks for the bottom-up setups, whereas the discharge volume was reproduced satisfactorily with all the process maps. However, irrespective of the process map used, the runoff peaks were simulated with a certain delay, and the falling limb of the hydrograph was overestimated, especially for the short-duration event. With the top-down setup, the modelling chain based on the GH11 maps reproduced the runoff peaks better than the other process maps, whilst the runoff volume was slightly underestimated, independent of the process map used.

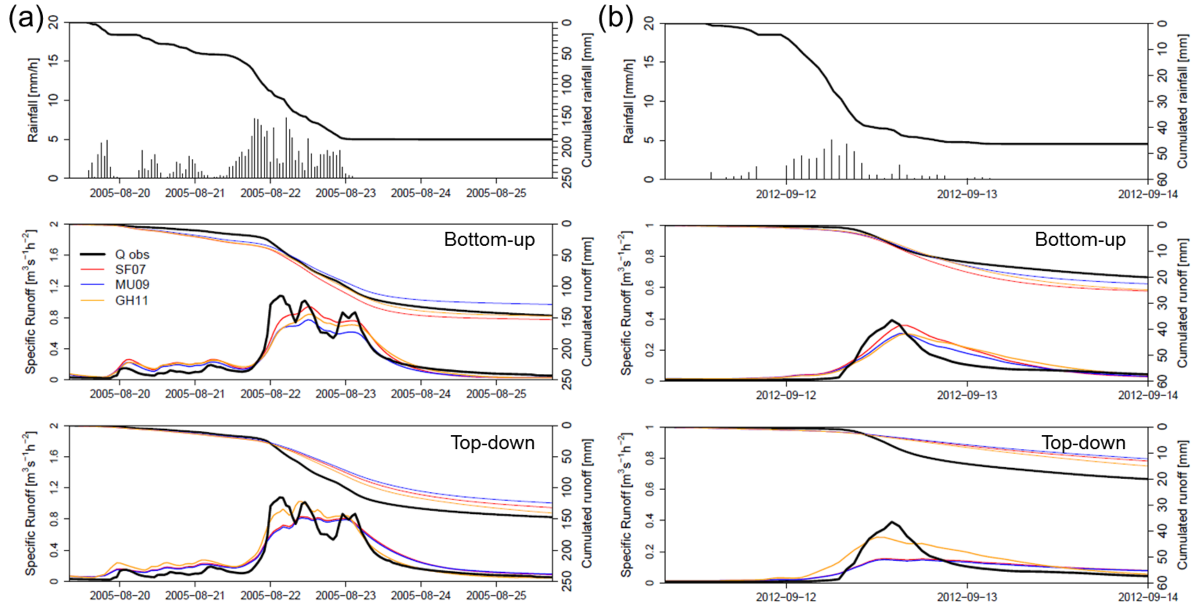

Figure III.7 Simulated runoff for the Emme catchment up to Emmenmatt during the long-duration event of August 2005 (a), and during the short-duration event of September 2012 (b), obtained from the different process maps and model parameterisations. The simulated hydrographs refer to the first run of the Monte Carlo simulation performed with the corresponding modelling chain combination. The SF07 map performed best with the bottom-up setup, whereas the GH11 map outperformed the other maps with the top-down setup.

The results for the other simulated events in the catchments investigated were analysed to gain further insights into the effects of using process maps with different involvement of expert knowledge (Figure III.8). With regard to the short-duration events (Figure III.8a), the bottom-up outperformed the top-down setup in all the catchments investigated with the exception of the Trueb sub-catchment, where none of the configurations reached satisfying results. Concerning the bottom-up configuration, SF07 maps performed best six times, i.e. slightly more often than the MU09 maps (four times), whereas GH11 never performed better than any of the other process maps. In contrast, when performed with the top-down parameterisation, the GH11 map obtained on average better results than the SF07 map, which, in turn, performed slightly better than MU09 map. With respect to the long-duration events (Figure III.8b), the performance difference between the two parameterisations was minimal on the main catchment (Emmenmatt), and on the Emme up to Eggiwil, whereas the combinations based on the bottom-up setup performed better than those based on the top-down setup on the Ilfis. None of the two parameterisations outperformed the other one on the Trueb sub-catchment, as they performed best once each. Similarly to what was observed for the short-duration events, none of the process maps outperformed the others within the bottom-up parameterisation. With regard to the top-down setup, the results obtained with the GH11 maps were on average better than those obtained with the other process maps on Emmenmatt and Eggiwil, whereas the MU09 maps performed best on the Ilfis sub-catchment. Again, no clear trend emerged on the Trueb sub-catchment. Over all, the performance spread between different runs of the same Monte Carlo simulation was considerably higher for the top-down than for the bottom-up configuration. Among the combinations based on the top-down experiment, the parameter uncertainty was found to be higher for GH11 maps than for the other process maps.

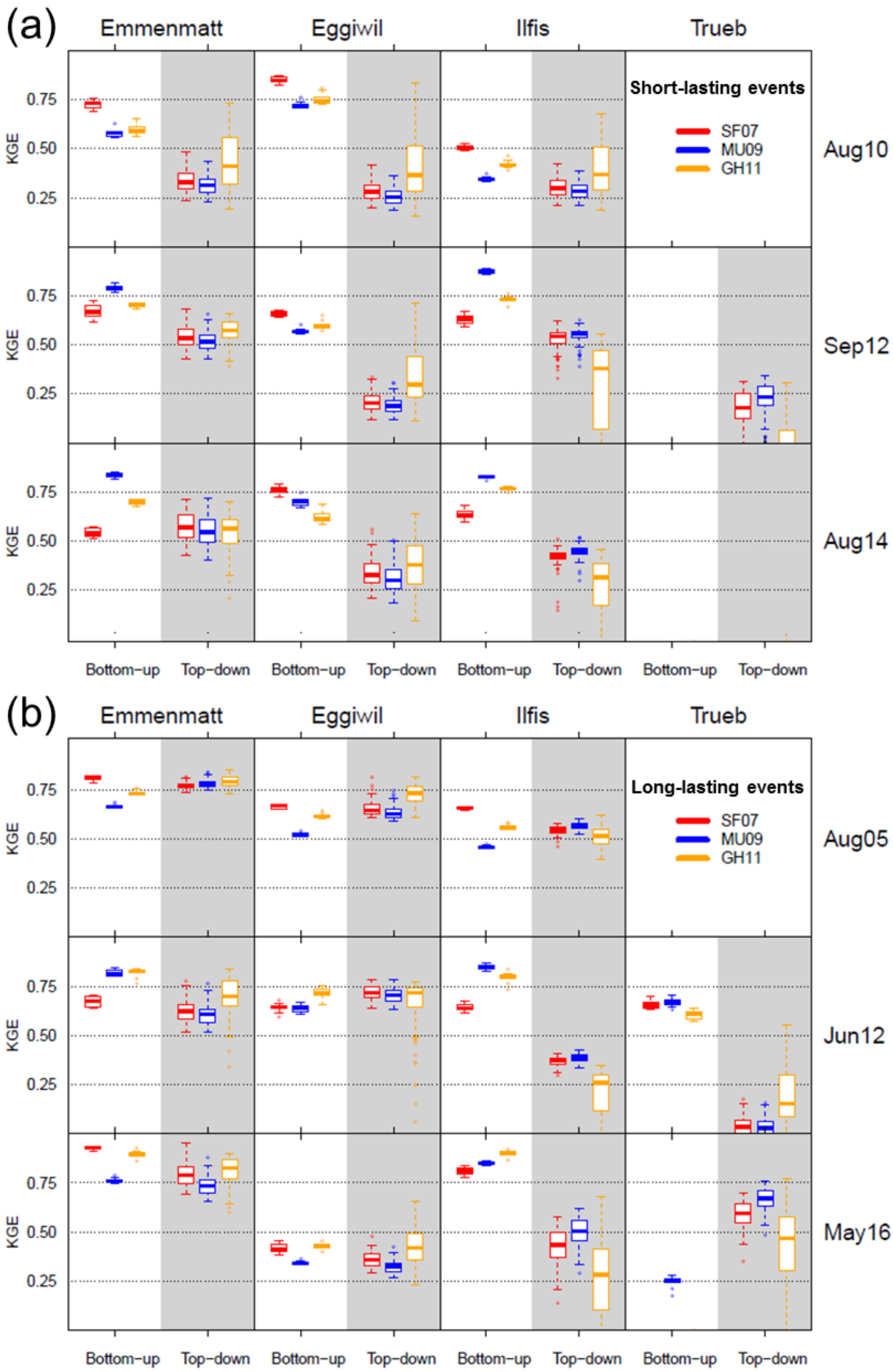

Figure III.8 Results from the short-duration (a) and from the long-duration events simulated on the catchments investigated using the benchmark modelling chain. The boxplots represent the simulation results of the bottom-up (white background) and of the top-down (grey background) parameterisations, whereas the coloured borders represent the different mapping approaches. Overall, the bottom-up performed better than the top-down setup during short-duration events, whereas no preference was found for long-duration events.

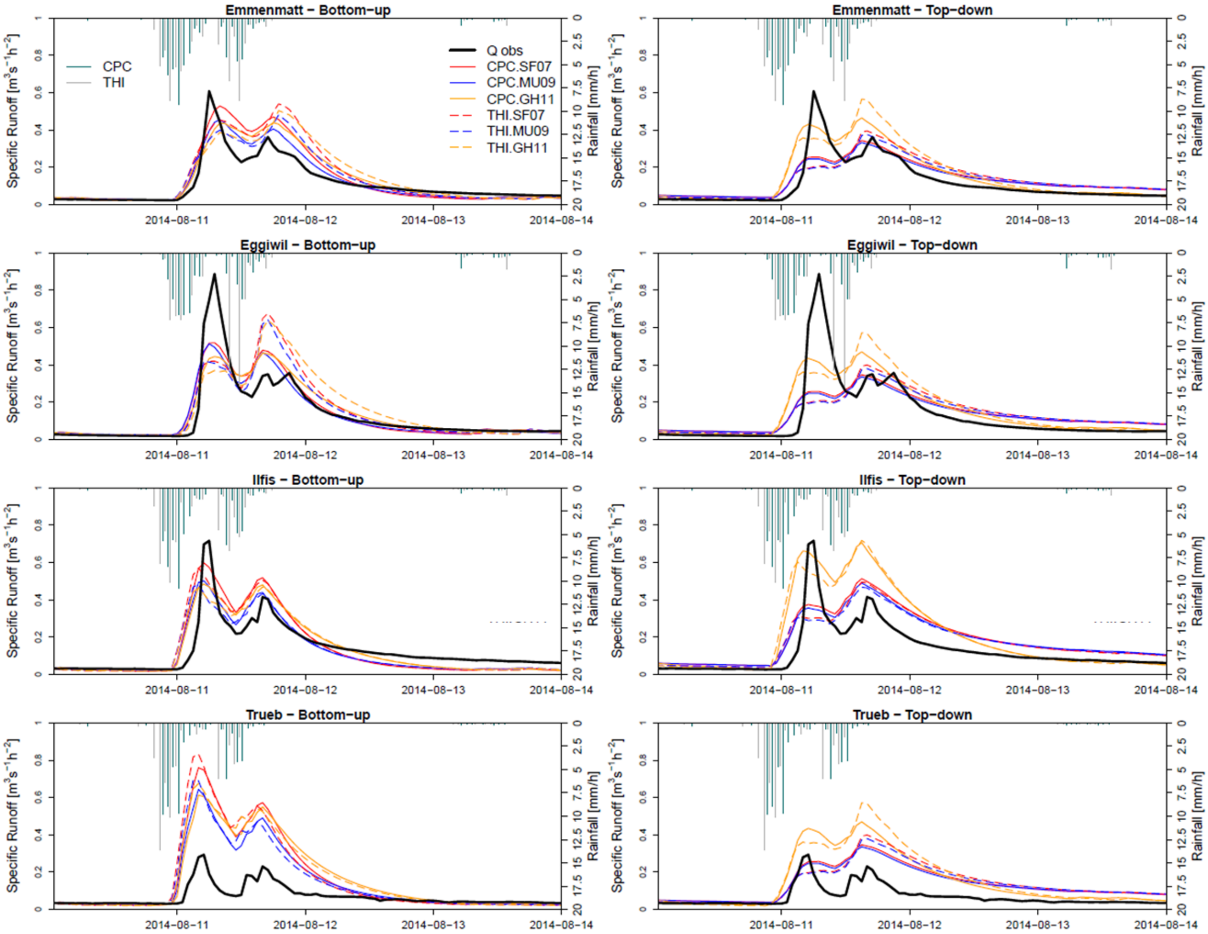

Figure III.9 Simulated runoff for the four study catchment during the long-duration event of May 2016, obtained from different input data (CPC = Combiprecip; THI = Thiessen polygons), process maps (SF07, MU09 and GH11), and model setups (bottom-up and top-down). The simulated hydrographs refer to the first run of the Monte Carlo simulation performed with the corresponding modelling chain combination. Errors linked with the input data (e.g. the overestimation of the second runoff peak at Emmenmatt and Eggiwil due to a higher input signal) can be distinguished from those more clearly linked with the model parameterisation.

A visual inspection of the hydrographs in Figure III.9 shows that feeding the modelling chains with rainfall data spatially interpolated with Thiessen polygons has a considerable effect on the runoff peaks and, consequently, on the simulated runoff volume. However, no effect was detected for the falling limb of the hydrographs. Both model setups systematically underestimate the runoff at the gauging station of Trueb, independent of the process map used.

More generally, forcing the modelling chains with rainfall data of lower quality generally decreased the model performance (Figure III.10), moderately for the main catchment and more markedly for Eggiwil and for the Ilfis sub-catchments. The Trueb sub-catchment is an exception, as the use of rainfall data of lower quality increased the model performance nearly everywhere, independent of the process map used. Averaging the Combiprecip data over the whole catchment (CPC.mean) had the lowest impact on the simulated runoff, irrespective of the parameterisation approach and process map used. In contrast, using data interpolated with IDW and Thiessen polygons led on average to considerable performance losses, irrespective of the model parameterisation, especially

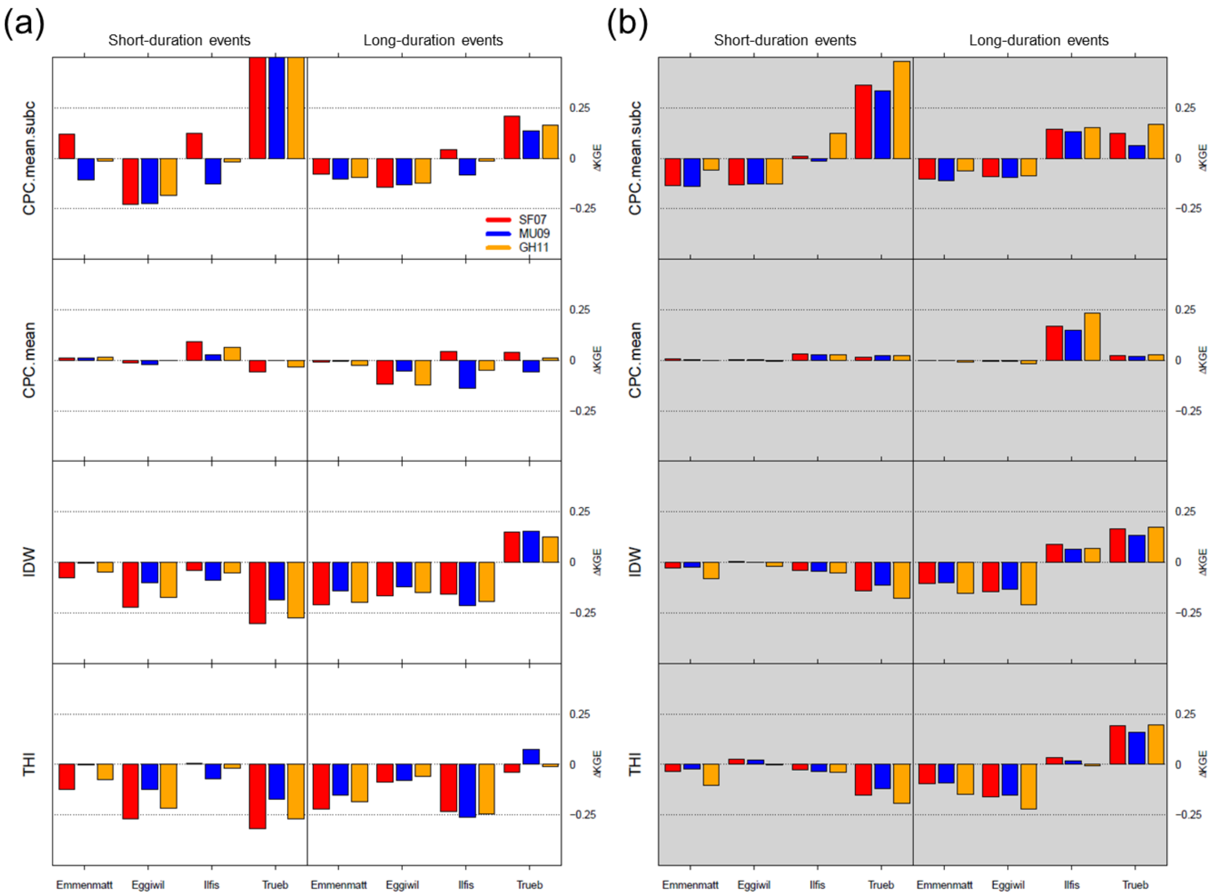

Figure III.10 Averaged KGE deviations from the benchmark modelling chain (i.e. driven by Combiprecip data) obtained with the bottom-up (a) and top-down (b) configurations. Each block corresponds to a specific modelling chain based on the rainfall data reported on the left (CPC = Combiprecip; IDW = inverse distance weighting; THI = Thiessen polygons), whereas the displayed event types are reported at the top. The bars represent the average performance difference obtained from Monte Carlo runs for each of the four study areas, whilst the colour of the bars represent the different mapping approaches. Overall, the performance deviations were higher for the bottom-up than for the top-down setup.

for short-duration events. The performance losses for short-duration events were higher for the bottom-up than for the top-down setup, whereas their magnitude was similar among the two setups for long-duration events. The most pronounced performance changes were found in the Trueb sub-catchment with the bottom-up setup forced with Combiprecip data averaged over the sub-catchments. The choice of process map appeared to have little effect.

Uncertainty significantly increased with the decrease in size of the sub-catchments according to the analysis of variance (ANOVA), whereas the most important source of uncertainty was the parameterisation and parameter allocation strategy (Figure III.11a). The smallest source of uncertainty was the hydrological downscaling technique, which was found to be responsible for a slight improvement in simulation skills (Figure S1). The influence of the process maps also increases with decreasing catchment size. However, when considering the two model configurations separately, the main uncertainty source varies depending on the catchment considered (Figure III.11b-c). With regard to

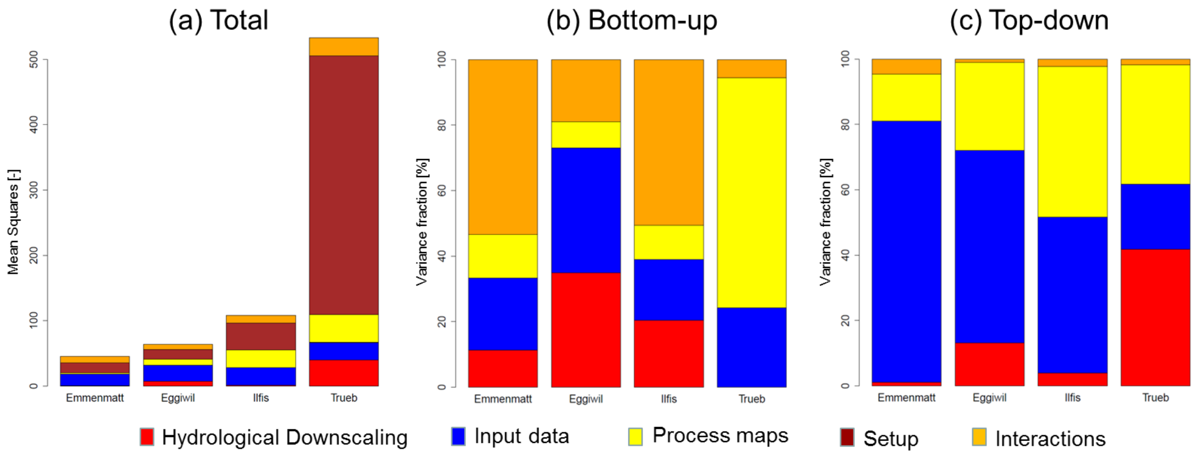

Figure III.11 Decomposition of the model performance (KGE) variance at the four gauging stations for all the modelling chain combinations (a), as well as for those based on the bottom-up (b) and top-down (c) configurations. Total uncertainty increases with increasing size of the catchments.

the bottom-up experiment, the interaction between input data and process maps was found to be the largest source of uncertainty in the main catchment (Emmenmatt) and in the Ilfis sub-catchment. In the Eggiwil sub-catchment, the hydrological downscaling techniques and the input data were responsible for the largest uncertainties, whereas, on the Trueb sub-catchment, the process maps accounted for most of the differences in performance. Concerning the top-down setup, the input data were responsible for the largest variance in the main catchment and in the Eggiwil and Ilfis catchments, whereas the process maps were increasingly responsible for uncertainty with decreasing size of the sub-catchments.

4. Discussion

The main purpose of this study was to test different implementations of expert knowledge in a process-based hydrological modelling framework, following the basic assumption that combining top-down and bottom-up thinking can improve flood predictions and potentially be applied in poorly gauged areas. Methods of different complexity were therefore tested for each step in the modelling process, including hydrological mapping, model parameterisation and parameter allocation. We wanted to find out whether the use of detailed expert knowledge during the mapping phase can improve simulation results, and how different levels of process knowledge interact with the model parameterisation and parameter allocation strategy when they are forced by precipitation products of different quality. In the following sections, we discuss what light our findings shed on the research questions.

4.1 Can more expert knowledge in the mapping phase increase model performance?

We tested the hypothesis that a more complex mapping approach leads to better simulation results with a benchmark modelling chain forced with the best grid-based rainfall data available in real-time for the whole of Switzerland, that is the Combiprecip product (Sideris et al., 2014). Recently, Antonetti et al. (2016) speculated on the added value of using as much of the available expert knowledge as possible for the hydrological classification. Our findings showed, the hypothesis can only be confirmed for the bottom-up setup, where the modelling chain combinations based on the most complex mapping approach (SF07) resulted in, on average, the highest performances in the study catchments. Conversely, no clear performance improvement was obtained by using SF07 maps with the top-down setup, irrespective of the event type considered. The best performances obtained with by the top-down setup and the GH11 map are most likely attributable to the lower number of classes in the GH11 approach (three instead of five), which allowed the model to be more flexible and consequently the hydrographs to be better reproduced, but not necessarily for the right reason (Kirchner, 2006). In fact, the exclusive use of topographical information for the DRP mapping combined with the top-down setup has been shown to work only in the main catchment and in the sub-catchment of Eggiwil. This suggests that combining the mapping method of Gharari et al. (2011) and the parameter allocation strategy of Gharari et al. (2014) is potentially worthwhile for specific types of catchment, especially those topography-controlled, whereas in other basins more complex mapping approaches need to be used (e.g. on Ilfis and Trueb). Fenicia et al. (2016) similarly found that a catchment classification based on geology led to better results than a classification based on HAND in the Attert catchment in Luxemburg.

The results obtained with the simplified mapping approaches (MU09 and GH11) were, on average, only slightly lower than those obtained with the SF07 maps. Therefore, as the effort needed to derive the simplified maps is substantially lower, using one of the two top-down mapping approaches investigated here may be the best choice in terms of cost-benefit. However, this conclusion is not acceptable from an experimentalist point of view. The results may seem acceptable at the gauging stations, but the local representation of the DRP mapped would most likely differ from that expected by an experimentalist. Topography alone cannot furnish information about the storage and infiltration capacity of soils, as Scherrer et al. (2007) pointed out. Therefore, the two top-down mapping approaches tend to overestimate the runoff contribution of steep slope and underestimate it on flat areas (Antonetti et al., 2016).

Modellers and experimentalists need to agree on what they mean by realism, and how much detail hydrologists should provide to achieve it. An exact reproduction of processes at the plot scale (e.g. exact localisation of macropores etc.) is of course unfeasible due to lack of data, and even knowledge, and the high computational effort such a level of detail would require (Beven, 2001, 2000; Semenova and Beven, 2015; Weiler and McDonnell, 2004). No experimentalist would therefore expect this level of detail from a process-based model at the catchment scale. However, in our opinion, the hydrological community should aspire to develop models able to reproduce processes in a “realistic” way (i.e. in agreement with the experimentalists’ expectation), at least at the sub-catchment or, even better, at the hillslope scale. This should be a feasible goal, especially considering how new measurements techniques continue to be developed and existing ones refined (Savenije and Hrachowitz, 2017). Such high requirements will probably challenge the validity of simplified mapping approaches and highlight the added value of the more complex ones. The availability of measured data for smaller sub-catchments, where the results of the mapping approaches differed greatly (e.g. in the upper part of the Eggiwil sub-basin), could have better emphasised the potential added value given by more accurate process maps. Future research will address this topic.

4.2 Bottom-up versus top-down model setup

Which model setup was more efficient in modelling the catchment systems investigated in this study? To answer this question, the model parameterisations and the parameter allocation strategies used are addressed separately.

The low performances of the top-down setups in simulating the short-duration events probably depend on the parameterisation approach chosen. The coupled parameterisation of runoff generation, concentration, and routing could well be responsible for the insufficiently fast reaction to high precipitation intensity, as, for instance, fast subsurface flow is basically not allowed to occur. With the bottom-up parameterisation, the underestimation of the falling limb of the hydrograph highlighted by the visual inspection of the hydrographs of Figure III.9 is ascribable to the poor representation of the runoff concentration by the bottom-up setup. However, the adaptation of the model structure, e.g. by introducing a function for the explicit consideration of the time lag due to the processes of runoff concentration and routing, was beyond the scope of this study.

Concerning the parameter allocation strategies, the very same low performances reached by the top-down setup during short-duration events could be also related to the modellers' tendency to set relational rules among parameter and fluxes of different classes. Although the definition of parameter and process constraints force the model to behave according to the modeller's perception of the catchment functioning, the parameter space defined by the initial parameter ranges of Viviroli et al. (2009b) was apparently still too large to ensure high performances with only 100 Monte Carlo runs. On the other hand, the bottom-up parameter allocation strategy led to overconfidence problems, as the measured runoff was only partially enveloped by the uncertainty bands defined by the different runs of the Monte Carlo simulation (Figure S2). This is directly ascribable to the definition of very narrow initial ranges for each parameter (Antonetti et al., 2017).

Considering the KGE deviations arising from the use of different forcing data furnished further insights into the setups tested here. The lower KGE deviations observed for the top-down setup showed that it can cope better than the bottom-up setup with uncertainties in the input data as it allows parameter values that can compensate for biases in the input data to be selected. This also explains the larger performance spreads reached by the modelling chains based on the top-down setup, as not all the parameter sets fulfil the requirements for compensating a biased forcing.

The bottom-up setup is therefore suitable for identifying of uncertainty sources. Once the extent and distribution of DRPs on a given catchment corresponds to the experimentalist's perception, which may still be biased, and once, for each output class of a process map, a proper parameterisation has been chosen, any remaining deviations of the simulated hydrograph from the measured hydrograph can be explained as arising from uncertainties either in the forcing data or in the measured discharge data.

4.3 Expert knowledge under uncertainty

The assumption that more reliable input data would have led to expert knowledge being more effectively applied in hydrological classification was investigated by varying the forcing data of the different modelling chain combinations. No clear trend was however identified among the different process maps. Even using the CombiPrecip data used for the benchmark modelling chain, which provide the best spatially distributed estimation of rainfall data available in real-time for the whole Switzerland, led to considerable uncertainties, especially with short-duration events, due to its spatially resolution (1 km^2) and problems linked with radar images (see also Antonetti et al., 2017). When the input data are of low quality (e.g. interpolated with simple approaches like IDW and Thiessen polygons), the way model performance can change is symptomatic of the presence of compensation effects within the model. For example, the largest deviations, which occurred in the Trueb sub-catchment, are attributable to the meteorological station on Napf, which is located at 1404 m a.s.l.. It only makes sense to regionalise the values from mountain stations if an elevation factor is taken into accounting, otherwise it may, as here, lead to a local overestimation of the precipitation and, consequently, of the discharge (Sevruk and Mieglitz, 2002; Sevruk, 1997).

Over the years, instead of refining the process maps by drawing on more knowledge in the mapping phase, the opposite occurred, and the uncertainty in the input data was used as an excuse for removing complexity from hydrological classifications. For example, Müller et al. (2009) developed their mapping approach based exclusively on information about topography, geology, and land use in order to simplify the method of Schmocker-Fackel et al. (2007), which is in turn a simplification of the manual mapping approach developed by Scherrer and Naef (2003) and is based on all the information available about a basin. Only two years later, Gharari et al. (2011) introduced a further classification approach based exclusively on topography. This oversimplification risk could be avoided by defining better the minimal criteria for “realism” a model should fulfil before claiming that it had improved realism.

4.4 Quantifying uncertainty sources

The analysis of variance (ANOVA) on the catchments investigated showed that the uncertainty linked with parameterisation and parameter allocation strategies was always at least comparable quantitatively with that originating from the input data. For the sub-catchments investigated, it was even greater. This suggests that the step in the modelling process in question has the highest potential for improvement. For two of the four catchments investigated, the uncertainty originating from the process maps was found to be comparable with that arising from the different input data. This means that, up to a certain catchment size, a proper mapping of processes is as important as the availability of reliable input data. The soil moisture data assimilated from PREVAH simulations could also represent an important source of uncertainty. Performing a virtual experiment where the catchments were assumed to be completely saturated at the beginning of each event led to large overestimations of the initial peaks during an event (Figure S3). However, with a view to an operational application of RGM-PRO, the data from the PREVAH simulations used in this study represent the best grid-based estimation of soil moisture available in real time (Horat, 2017). Using of soil moisture data from other grid-based models was beyond the scope of this study.

Results from the ANOVA also showed a considerable increase in uncertainty with decreasing size of the sub-catchments, as Hellebrand et al. (2011) also found and attributed to a wrong choice of the calibration catchment. The poor performances of the bottom-up setup in the Trueb sub-catchment, which originated the large uncertainty shown in Fig. 11, can, however, be attributed to the low quality of the measured discharge data. The measurement accuracy of the gauging station there has already been questioned in another study (Scherrer AG, 2012), and may of course compromise the potential benefits of using more complex process maps. Checking the rating curve of the gauging stations was, however, beyond the scope of this study.

4.5 Limitations of this study

Some aspects to be investigated during future research include working towards a more thorough modelling system by investigating not only the runoff formation process but also other fluxes that can dominate in a basin such as evapotranspiration and interception. Investigating the influence of expert knowledge on the parameterisation of these processes was beyond the scope of this study, but could represent a direction for future research. We restricted our modelling to an event-based runoff generation module because the SF07 maps and the MU09 maps had been developed with a focus on floods. The simulation time step of one hour for investigations on floods is limiting especially when simulating short-duration events (Steinbrich et al., 2016). Sideris et al. (2014) proposed a disaggregation scheme for the generation of precipitation estimates with a resolution of five and ten minutes, but this involves still large uncertainties, and the hourly aggregated data was found to produce higher skill scores in the validation phase. We therefore only included hourly forcing in this study. The equations governing the storage behaviour were solved with an explicit Euler scheme, which has already been found to be responsible for uncertainty in other studies due to the numerical approximations involved (Kavetski and Clark, 2010). To address this issue, an adaptive number of sub-hourly integration steps was introduced according to the intensity of water reaching the upper-zone runoff storage SUZ.

No soft data from experimentalists' campaigns was used to inform or validate our model. This approach was demonstrated to be valuable to pursue the dialogue between modellers and experimentalists (Seibert and McDonnel, 2002). For the evaluation of the modelling chain combinations, we used the KGE metric exclusively instead of multiple validation criteria suggested by several authors (e.g. Güntner et al., 1999; Krause et al., 2005; Moussa and Chahinian, 2009; Seibert and McDonnell, 2002; Uhlenbrook and Leibundgut, 2002; Weiler and McDonnell, 2007). The KGE is, however, a comprehensive objective function that takes into account both peak and volumetric errors. It was therefore considered suitable for event-based model evaluation. Finally, to generalise the findings of this study, the number of catchments and events investigated should be increased considerably. For example, investigating catchments with contrasting reactions to heavy rainfall should provide more support for using more complex mapping approaches to identify the extent and distribution of DRPs.

5. Conclusions

Recent calls to combine bottom-up and top-down reasoning to improve the realism of process-based hydrological models were what motivated this study. We wanted to obtain insights into how to best use expert knowledge, given unavoidable uncertainties. First, we investigated how applying different degrees of expert knowledge in landscape classification affects the final outcome of hydrological simulations. We compared two different setups (i.e. parameterisation and parameter allocation strategies): the first is based on experimentalists' (bottom-up) reasoning, and the second is driven by a modellers' (top-down) thinking. We then looked at how performance varied with different levels of uncertainty in the forcing data before finally quantifying the fraction of variance explained by each uncertainty source.

The main findings of the study were:

- Using complex process maps with high involvement of expert knowledge adds little potential value due to large uncertainties occurring even with the best forcing data available in real-time and in the measured discharge data. Performance using simplified mapping approaches was also satisfactory, especially for long-duration events.
- The bottom-up setup performed better on average than the top-down setup in the catchments investigated, independent of the process map used. The top-down setup was able to accommodate biases in the precipitation data at the expense of exactly identifying sources of uncertainty. Conversely, the bottom-up setup can be used diagnostically to identify uncertainty sources, but had overconfidence problems due to an overly narrow a priori definition of parameter ranges.
- The uncertainty linked with the process maps and, consequently, the importance of a realistic representation of the spatial distribution of processes, increased with decreasing size of the catchments.

In conclusion, modellers and experimentalists need to reach agreement on what they mean by "model realism", especially concerning the level of detail. In our opinion, a catchment scale model should be able to reflect the real distribution of dominant runoff processes up to the hillslope scale. More accurate process maps can help to achieve this goal.

Data Availability

MU09 maps, GH11 maps and RGM-PRO are available from Manuel Antonetti (manuel.antonetti@wsl.ch), and the PREVAH soil moisture estimations from Massimiliano Zappa (massimiliano.zappa@wsl.ch). The GIS data used for deriving the MU09 maps and GH11 maps can be obtained undo license from the Federal Office of Topography swisstopo, whereas the SF07 maps were provided by Scherrer AG and SoilCom GmbH (contact the authors for help in accessing them). The runoff data is available from the Swiss Federal Office for the Environment and the Canton of Bern, and the precipitation data from the Swiss Federal Office of Meteorology and Climatology MeteoSwiss (free of charge for scientific purposes).

Acknowledgements

We thank the Swiss Federal Office for the Environment (FOEN) for funding the PhD project of the first author, the Swiss Federal Office of Meteorology and Climatology MeteoSwiss for providing the precipitation data, and FOEN and the Canton of Bern for providing the observed runoff series. We are also very grateful to Michael Margreth and Simon Scherrer for providing the SF07 maps of the catchments investigated and to Silvia Dingwall for language feedback.

Supporting Material

See Figure S1, Figure S2, and Figure S3.

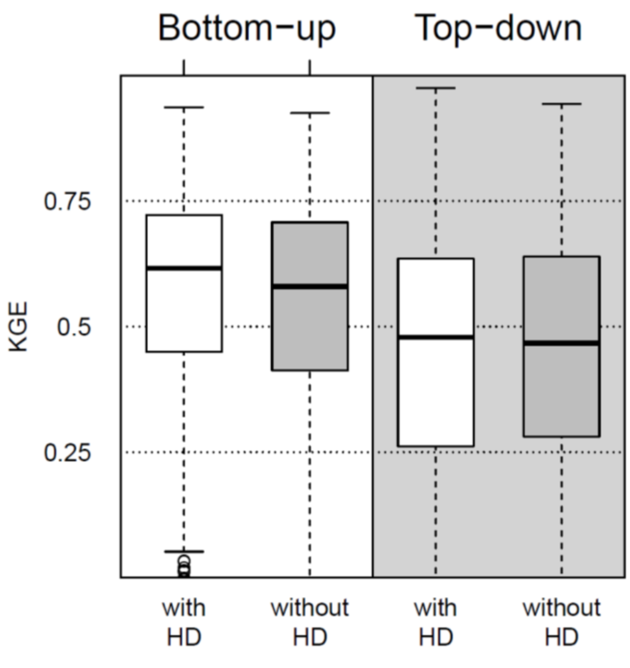

Figure S1. Comparison of the simulation results obtained with and without hydrological downscaling (HD) of the initial conditions by the modelling chains based on either the bottom-up or the top-down configuration. HD slightly increased both the best and average performance of the model setups.

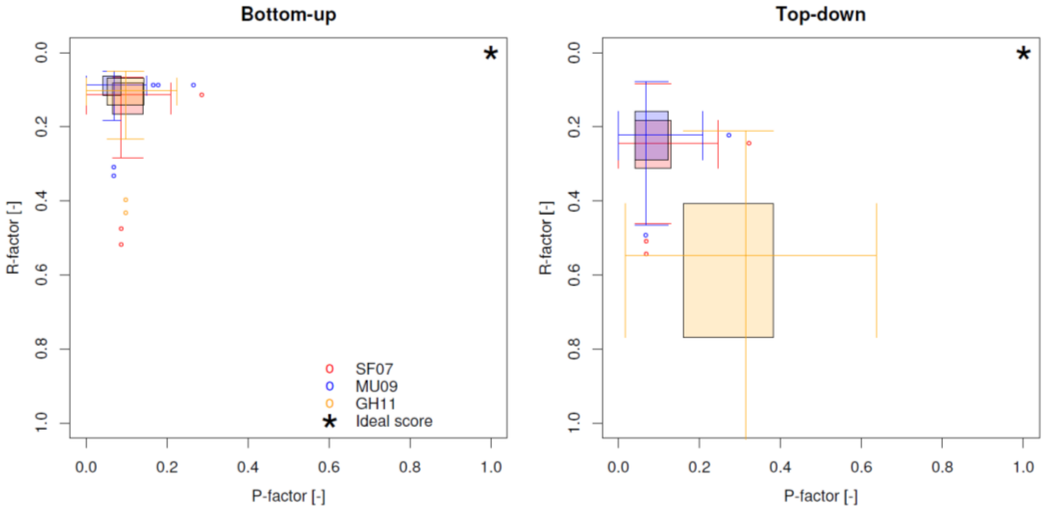

Figure S2. Values of P-factors (x axis) and R-factors (y axis) calculated for the different process maps with the bottom-up and top-down setups. The ideal score (i.e. P-factor = 1 and R-factor = 0) is represented with a black asterisk. Whilst the process maps performed similarly with the bottom-up setup, the observed runoff was best bracketed by simulations obtained with the GH11 maps and the top-down setup, but at the expense of a wider uncertainty band (i.e. lower R-factors).

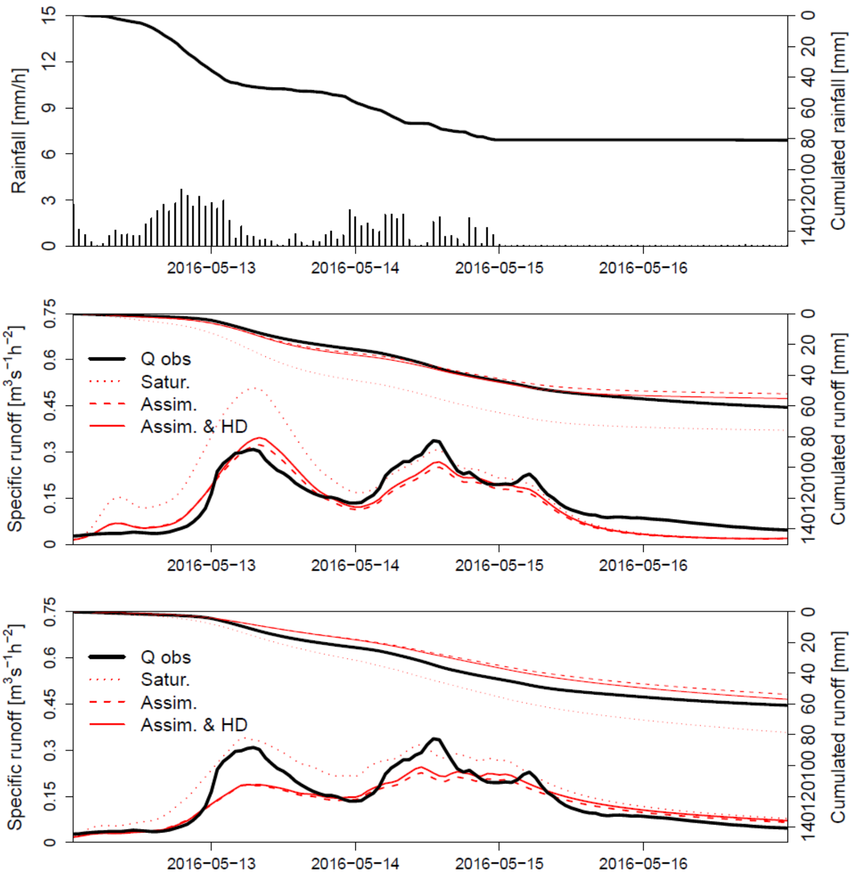

Figure S3. Influence of the soil moisture initial conditions on the simulated runoff for the Emme up to Emmenmatt during the long-duration event of May 2016 obtained with the bottom-up (a) and top-down (b) setup. The simulated hydrographs refer to the first run of the Monte Carlo simulation performed with SF07 map and with Combiprecip as forcing. The saturated initial conditions led to a significant overestimation of runoff at the beginning of the simulations, whereas the hydrological downscaling barely affected the simulation results.

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AI Überprüfung von einem prozessnahen Abflussbildungsmodul auf der Hangskale und für klein- und mesoskalige Gebiete

The results presented at the 4th workshop on rainfall-runoff modelling, which was held in Trier (Germany) in October 2015, are reported in the following appendix. After a simplified peer-review process, this contribution was published (in German) for the "Forum für Hydrologie und Wasserbewirtschaftung" under the reference:

Antonetti, M., Scherrer, S., Kienzler, P.M., Margreth, M., Zappa, M. 2016. Überprüfung eines prozessnahen Abflussbildungsmoduls auf der Hangskale und in klein- und mesoskaligen Gebieten. In Forum Für Hydrologie Und Wasserbewirtschaftung 36.16: 63–74.

Manuel Antonetti[a,b], Simon Scherrer[c], Peter Matthias Kienzler[c], Michael Margreth[d], Massimiliano Zappa[a]

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[a] Eidg. Forschungsanstalt WSL, Zürcherstrasse 111, 8903 Birmensdorf, Schweiz.

[b] Geographisches Institut, Universität Zürich, Winterthurerstrasse 190, 8057 Zürich, Schweiz.

[c] Scherrer AG, Schönmattstrasse 8, 4153 Reinach, Schweiz.

[d] SoilCom GmbH, Probusweg 22, 8057 Zürich, Schweiz.

Zusammenfassung

Eine prozessnahe Routine für das konzeptionelle, räumlich verteilte, hydrologische Modell PREVAH wurde entworfen, welche aus einem Bodenwasserspeicher, einem Linearspeichersystem für die Abflussbildung und einem Basisabflussspeicher besteht. Die Innovation liegt in der Verwendung von Abflusstypenkarten und in der Sub-Parametrisierung der Abflussbildungsprozesse, indem jedem Abflusstyp ein entsprechendes Linearspeichersystem zugeordnet wird. Das Modell wird durch kontinuierliche PREVAH-Simulationen initialisiert, indem die Bodenfeuchte eingelesen und in Abhängigkeit von den verschiedenen Abflusstypen umverteilt wird. Beregnungsversuche wurden nachgerechnet, bei welchen die Abflussprozesse von kleinen homogenen Flächen bei klar definierten künstlichen Niederschlägen unterschiedlicher Intensität untersucht wurden. Das ermöglichte es, optimierte Modellparameterbereiche a priori festzulegen. Das neue Modell wurde in zwei kleinskaligen Einzugsgebieten in den Schweizer Voralpen sowie in zwei mesoskaligen Einzugsgebieten im Schweizer Mittelland getestet und mit dem traditionellen PREVAH verglichen.

Das neue Modell zeigte eine gegenüber dem traditionellen PREVAH vergleichbare Leistung in der Kalibrierungsperiode, während der gemessene Abfluss in der Validierungsperiode besser simuliert werden konnte. Zudem gab das neue Modell eine realistischere Verteilung der Prozesse auf den Einzugsgebieten wieder.

1. Einführung

Die gegenwärtigen Module zur Beschreibung der Abflussbildung in konzeptionellen hydrologischen Modellen sind stark auf Kalibrierungen angewiesen. Denn sie simulieren den Abfluss in Einzugsgebieten ohne Messungen meist nicht mit der erforderlichen Genauigkeit. Flüsse und Bäche können in der Tat sehr unterschiedlich auf Starkniederschlag reagieren. Auf manchen Böden infiltriert Regen kaum und fliesst rasch ab, auf anderen Böden jedoch kann der gesamte Regen infiltrieren und wird entweder gespeichert oder gelangt auf unterirdischen Fliesswegen mehr oder weniger verzögert zum Abfluss. Entscheidende Faktoren sind das Infiltrationsvermögen und die Speicherfähigkeit der Böden im Einzugsgebiet.

In den letzten Jahren wurden deutliche Fortschritte hinsichtlich des Prozessverständnisses erzielt. Basierend auf Beregnungsversuchen (SCHERRER 1997; KIENZLER 2007) wurden Kriterien festgelegt, unter welchen Standorteigenschaften welcher Abflussprozess zu erwarten ist (SCHERRER & NAEF 2003). Darauf aufbauend wurde ein Bestimmungsschlüssel für die Kartierung hochwasserrelevanter Flächen entwickelt (SCHERRER AG 2006). Welche Abflussprozesse an einem Standort auftreten und welcher davon dominiert, hängt von der Mächtigkeit, Struktur und Oberfläche des Bodens, vom geologischen Untergrund, von der Topographie, der Landnutzung und dem Niederschlag ab (SCHERRER & NAEF 2003). Die Prozesse, welche eine ähnliche Reaktion auslösen, werden in sogenannte Abflusstypen zusammengefasst (Tabelle 1).

Tab. 1: Übersicht der verschiedenen Abflussbildungsprozesse und deren Aufteilung in Abflusstypen (AT). Verändert nach NAEF et al. (2000).

Fliessweg	Prozessgruppe	Abk.	Intensität des Abflussprozess	AT
Oberfläche	Hortonscher Oberflächenabfluss	HOF1	Sofortiger Oberflächenabfluss als Folge von Infiltrationshemmnissen	1
		HOF2	Leicht verzögerter Oberflächenabfluss als Folge von Infiltrationshemmnissen	1
	Gesättigter Oberflächenabfluss	SOF1	Sofortiger Oberflächenabfluss als Folge sich schnell sättigender Flächen	1
		SOF2	Verzögerter Oberflächenabfluss als Folge sich sättigender Flächen	2
		SOF3	Stark verzögerter Oberflächenabfluss als Folge sich langsam sättigender Flächen	4
Unterirdisch	Laterale Fliessprozesse im Boden	SSF1	Sofortiger Abfluss im Boden	2
		SSF2	Verzögerter Abfluss im Boden	3
		SSF3	Stark verzögerter Abfluss im Boden	4
	Tiefensickerung	DP	Tiefensickerung ins Grundwasser	5

Ziel dieser Studie ist es zu untersuchen, wie die Verwendung von räumlich verteilten Prozessinformationen aus sogenannten Abflusstypenkarten (ATK) zur Reduzierung des Kalibrierungsbedarfs und somit zur Verminderung der Unsicherheit hydrologischer Simulationen dienen kann. Insbesondere für die Vorhersage bzw. Abschätzung von Extremereignissen ist diese Vorgehensweise sehr vielversprechend. Für die Ver-wirklichung dieses Konzeptes wurde ein prozessnahes Abflussbildungsmodul entwickelt, welches von „grossräumigen" PREVAH-Simulationen aktiviert und initialisiert wird und welches lokale Gewitterhochwasser mit höherer räumlicher und zeitlicher Auflösung zu simulieren imstande ist.

In den folgenden Kapiteln werden die Ergebnisse der Studie wie folgt dargestellt. In Kapitel 2 wird auf die Strategie zur Anwendung von ATK in PREVAH eingegangen. Kapitel 3 beschreibt die Parametrisierung des prozessnahen Moduls anhand von Beregnungsversuchen, während in Kapitel 4 beide Modelle – das traditionelle PREVAH und das neue prozessnahe Abflussmodul - in vier Einzugsgebieten verschiedener Grösse getestet werden. In Kapitel 5 werden die Schlussfolgerungen gezogen.

2. Das prozessnahe Abflussbildungsmodul

Abbildung 1 zeigt die angewandte Strategie zur Integration von Prozessinformation in PREVAH mittels der Entwicklung eines prozessbasierten Abflussbildungsmoduls. Um die Verwendung räumlich verteilter meteorologischer Daten der Meteoschweiz („CombiPrecip-Produkt", SIDERIS et al. 2014) und Abflusstypenkarten als Inputdaten für das Modell zu ermöglichen, wurde eine gegitterte Diskretisierung mit einer Auflösung von 500 m verwendet.

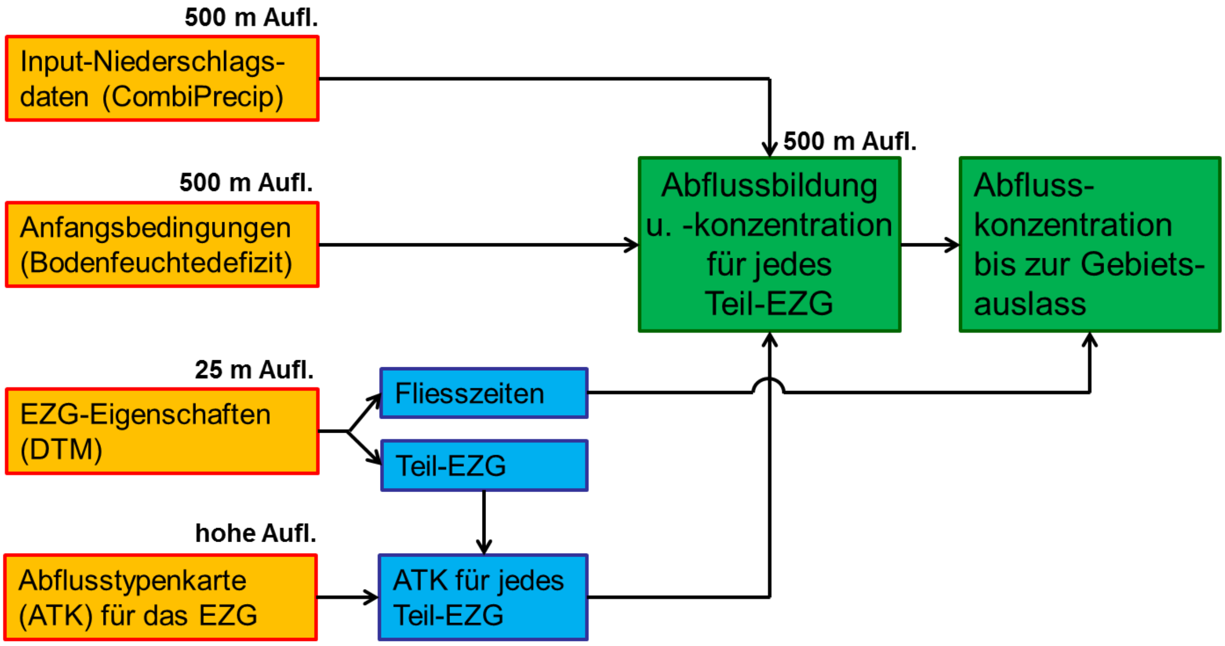

Abb. 1: Das Flussdiagramm stellt die verfolgte Strategie zur Integration von Prozessinformation im hydrologischen Modell dar.

Aus einem Höhenmodell (DTM) wird das gesamte Untersuchungsgebiet in verschiedene, bis zu 0.5 km2 grosse **Teil-EZG** unterteilt. Für jeden Auslass der berechneten Teil-EZG wird eine charakteristische **Fliesszeit** in den Gerinnen bis zum Gebietsauslass mit dem TANALYS-Tool (SCHULLA 1997) berechnet. Die **Abflussbildung** und die **Abflusskonzentration** auf der Landoberfläche bis zum Teilgebietsauslass werden somit gekoppelt berechnet. Das Routing im Gerinne bis zum Gebietsauslass erfolgt danach separat anhand eines Linearspeicher-Ansatzes.

In einer sog. „DRP-Matrix“ (Tabelle 2) werden die Anteile der Abflusstypen jeder Zelle zu 500x500 Meter-grossen Zellen zusammengefasst. Dazu wurde ein Werkzeug programmiert, das die DRP-Matrix aus einer hoch aufgelösten Abflusstypenkarte erzeugt (Details zum DRP-Konzept in MÜLLER et al. 2009 und in SCHMOCKER-FACKEL et al. 2007). Dieses Verfahren ermöglicht einen vernünftigen Rechenaufwand und vermeidet gleichzeitig Informationsverluste durch die Gitterauflösung.

Tab. 2: Eine sogenannte „DRP-Matrix“ soll für jede Zelle Auskunft über die Anteile der Abflusstypen geben.

Zelle	Abflusstyp 1 [%]	Abflusstyp 2 [%]	Abflusstyp 3 [%]	Abflusstyp 4 [%]	Abflusstyp 5 [%]
1	5	0	50	30	15
2	0	17	3	55	25
…					
n	0	2	60	20	18

Abbildung 2a zeigt die gegenwärtige, konzeptionelle Struktur des Abflussbildungsmoduls von PREVAH (VIVIROLI et al. 2009a). In den Bodenwasserspeicher (SSM) und in das Linearspeichersystem für die Abflussbildung (SUZ) gehen der Bestandesniederschlag Pb [mm/h] und, falls vorhanden, das Schmelzwasser der Schneedecke ein. Ein Exponentialparameter CBETA teilt die Anteile des Bestandesniederschlags zwischen den beiden Speichern auf.

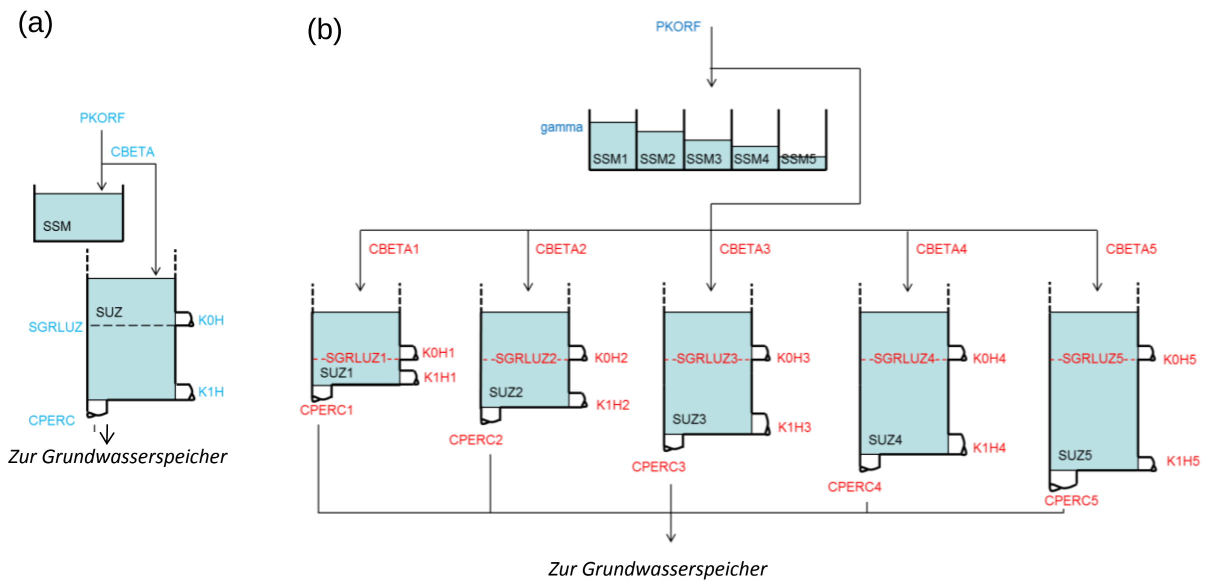

Abb. 2: (a) Das traditionelle Abflussbildungsmodul von PREVAH. Verändert nach VIVIROLI et al. (2009a); (b) Das prozessbasierte Abflussbildungsmodul. Rote bzw. blaue Beschriftungen beziehen sich auf abflusstyp- bzw. zellenbezogene Parameter.

Der Ausgang des Bodenfeuchtespeichers SSM führt in den Abflussspeicher SUZ. Von diesem gehen zwei Ausgänge raus, einerseits der schnelle Oberflächenabfluss und andererseits der verzögerte Zwischenabfluss im Boden. Diese zwei Auslässe werden durch zwei Speicherkonstanten K0H bzw. K1H gesteuert, während ein Speicher-grenzwert SGRLUZ zur Aktivierung des oberirdischen Abflusses dient. Zudem führt eine Versickerungskomponente mit einer maximalen Intensität CPERC in die unteren Grundwasserspeicher, welche verschiedene Grundwasserkomponenten bezeichnen. Abflussbildung, Abflusskonzentration und Routing werden gekoppelt berechnet. Dies verunmöglicht zuverlässige Simulationen mit dem traditionellen PREVAH in un-gemessene Gebiete, da die Speicherkonstanten stark von EZG-Eigenschaften wie z.B. Gebietsgrösse oder Gerinnedichte abhängen.

Für das prozessbasierte Abflussbildungsmodul wurde - in Anlehnung an die traditionelle Struktur von PREVAH - eine Modellstruktur entworfen, die aus einem Bodenwasserspeicher (Abbildung 2b, oberste Speichergruppe), einem Linearspeichersystem für die Abflussbildung (Abbildung 2b, untere Speichergruppe) und einem Grundwasserspeicher besteht. Die Innovation liegt in der Sub-Parametrisierung der Abflussprozesse, indem jedem Abflussbildungstyp ein entsprechendes Linearspeichersystem für jede Zelle zugeordnet wird. Ausgehend von der Annahme, dass schnell beitragende Flächen einen höheren Sättigungsgrad als langsam beitragende Flächen aufweisen, wurde die Bodenfeuchte um einen Faktor „gamma“ zwischen den verschiedenen Abflusstypen verteilt.

Tab. 3 Übersicht über die Beregnungsversuche mit Angaben zum Standort (Ls = Landschaft, VA = Voralpen, OG = Oberrheingraben, ML = Mittelland; DRP = „Dominant Runoff Process", dominanter Abflussbildungsprozess; RT = „Runoff Type", Abflusstyp; SOF = „Saturation Overland Flow", gesättigter Oberflächenabfluss; SSF = „Subsurface Flow", Fliessprozess im Boden; DP = „Deep percolation", Tiefensickerung). Verändert nach SCHERRER (1997) und KIENZLER (2007).

Beregnungsversuch	Ls.	Bodenform	Ausgangs-material	Vegetation, Nutzung	Neigung	DRP (RT)
Bilten	VA	Hanggley	Nagelfluh und Bergsturz-material	lichter Erlen- und Fichten-Jungwald	31%	SOF1 (1)
Therwil (Nachversuch)	OG	sandige Braunerde	Sandstein	extensive Weidenutzung	23%	SOF2 (2)
Willerzell-Hang (2x)	VA	sandige Braunerde	Sandstein	extensive Weidenutzung	55%	SSF2 (3)
Therwil	OG	sandige Braunerde	Sandstein	extensive Weidenutzung	23%	SOF3 (4)
Reiden	ML	Braunerde	Sandstein	Weide	40%	DP (5)

3. Modellparametrisierung

Eine wichtige Voraussetzung für die Übertragbarkeit des Modells in ungemessene Gebiete besteht darin, dass die Parameter für die Sättigung und Entwässerung der Speicher apriori so festgelegt werden, dass sie eine möglichst hohe Allgemeingültigkeit haben und somit auf möglichst viele Landschaften, Böden und Gesteinsformationen unverändert übertragen werden können. Die Innovation des prozessnahen Abflussbildungsmodul liegt deshalb in der „a priori" Festlegung von Parameter-intervallen: Wertebereiche für den Infiltrationsparameter CBETA sowie für den Speichergrenzwert des oberirdischen Abflusses SGRLUZ können in Abhängigkeit von Prozesstyp bzw. -intensität „a priori" bestimmt werden. Dies gilt auch für die Speicherkonstanten des oberirdischen Abflusses K0H und des unterirdischen Abflusses K1H sowie für die maximale Perkolationsintensität CPERC. Die Parameterbereiche werden so bestimmt, dass die Abflussreaktion der HOF-, SOF-, SSF- und DP-Flächen möglichst genau und allgemein gültig berechnet werden kann. Zu diesem Zweck wurden ausgewählte Beregnungsversuche nachgerechnet, die zur Untersuchung der Abflussprozesse auf kleinen homogenen, ca. 60 – 120 m^2 grossen Flächen mit klar definierten künstlichen Niederschlägen unterschiedlicher Intensität von SCHERRER (1997) und KIENZLER (2007) durchgeführt wurden (Tabelle 3).

Ausgehend von der Annahme, dass auf jeder Beregnungsfläche nur ein dominanter Abflussbildungsprozess auftritt, wurden die Parameterbereiche jedes Abflusstyps anhand von einer Montecarlo-Simulation mit 10000 Läufen eingegrenzt. Zu diesem Zweck wurde eine 1D-Version des prozessnahen Moduls mit einer zeitlichen Auflösung von 10 Minuten verwendet. Abbildung 3 stellt die Ergebnisse dieser Optimierungs-durchläufe dar. Es ist nicht überraschend, dass mit zunehmender Breite des optimierten Wertebereiches die Sensitivität der Parameter abnimmt. Im Fall vom Abflusstyp 5 (Tiefensickerung) sind beispielsweise die Speicherkonstanten nicht sensitiv, da dieser Abflusstyp so definiert ist, dass das Wasser ausschliesslich in die unteren Grundwasser-speicher fliesst.

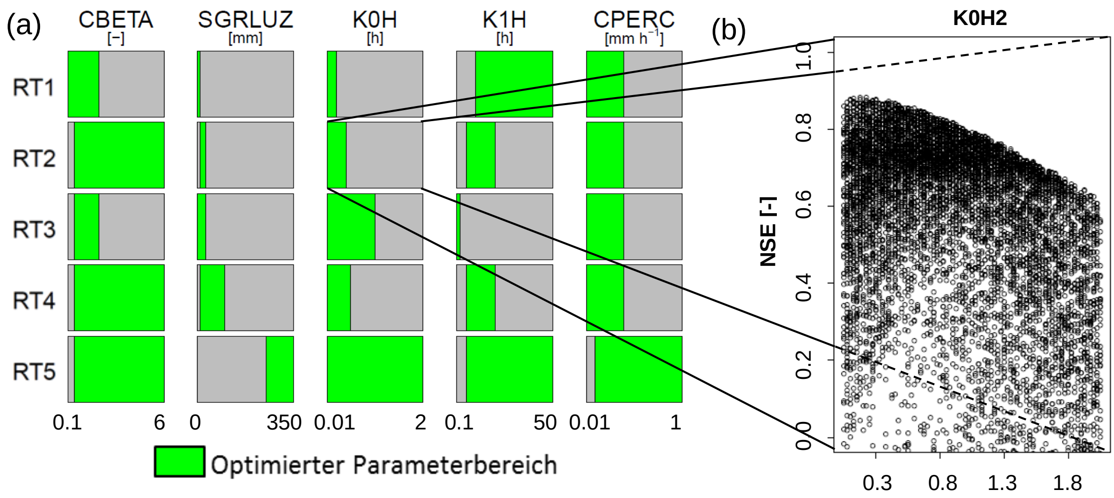

Abb. 3: (a) Parameterbeiche für jeden Abflusstyp (RT1-5), optimiert anhand der Nachrechnung von Beregnungsversuchen. (b) Beispiel der Optimierung des Parameterbereichs K0H für den Abflusstyp 2. NSE = „Nash-Sutcliffe Efficiency“

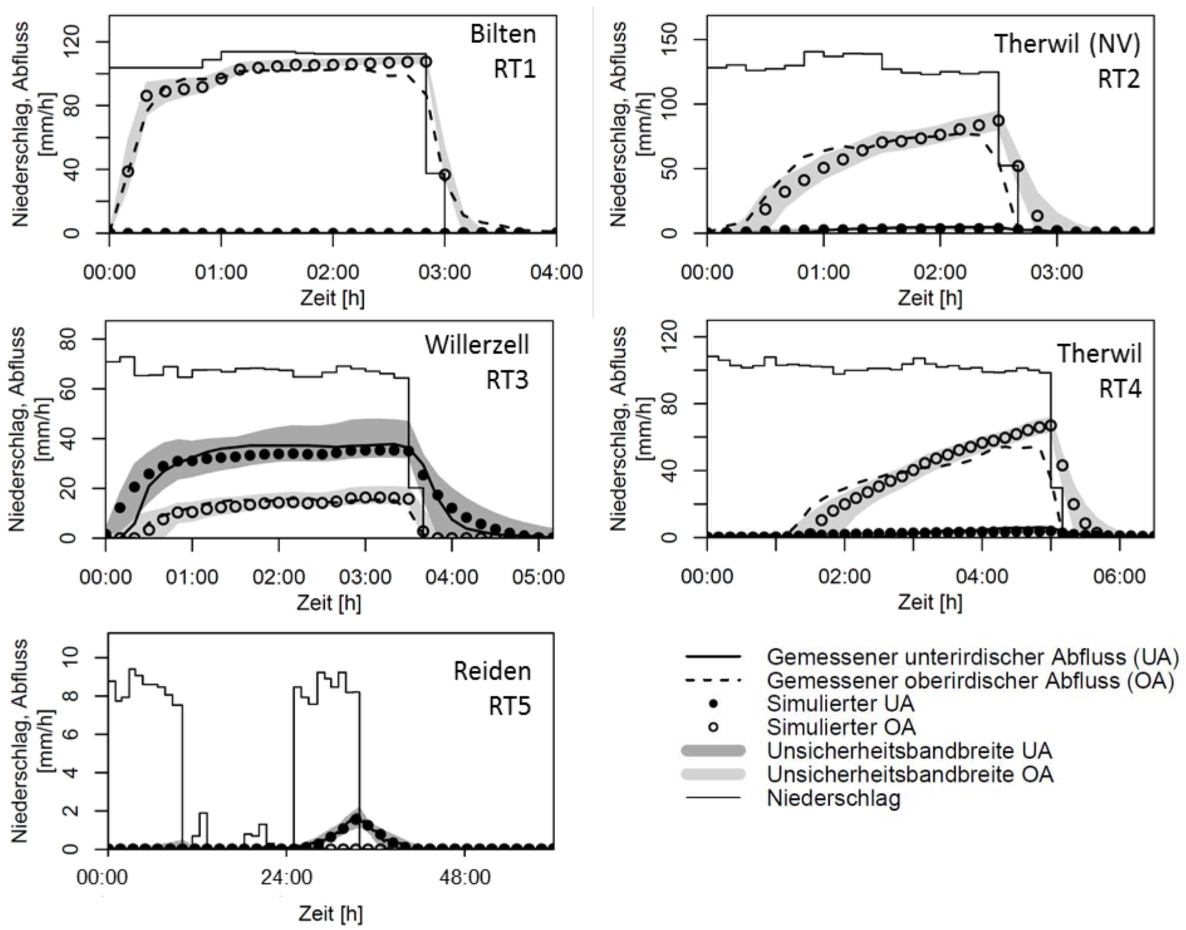

Abb. 4: Gemessene und nachgerechnete Abflussganglinien der in Tabelle 3 aufgelisteten Beregnungsversuche. Die Unsicherheitsbandbreiten umfassen den simulierten Abfluss der beste 100 Läufe.

Eine klare Unterscheidung ist zwischen schnell bis leicht verzögert beitragenden Flächen und sehr verzögert bis nicht beitragende Flächen festzustellen, wo den Speichergrenzwerten SGRLUZ geringe bzw. sehr grosse Werte zuerkannt werden. Diese a priori definierten Parameterbereiche sollen zur Differenzierung der Beiträge der verschiedenen Abflusstypen während der Abflussbildungsberechnung im prozessnahen Modell dienen.

Sowohl der oberirdische als auch der unterirdische Abfluss der Beregnungsversuche konnten in zufriedenstellender Weise nachgerechnet werden (Abbildung 4).

4 Übertragbarkeit auf klein- und mesoskalige Einzugsgebiete

4.1 Die Untersuchungsgebiete

Für diese Studie wurden zwei kleinskalige EZG in den Schweizer Voralpen sowie zwei mesoskalige EZG im Schweizer Mittelland ausgewählt (Abbildung 5). Der Sperbelgraben und der Rappengraben liegen wenige Kilometer voneinander entfernt im steilen Emmental. Diese kleinen EZG (ca. 0.5 km^2) liegen in der Napf-Nagelfluh, die eine mittlere bis geringe Durchlässigkeit aufweist (BAFU 2015). In beiden Gebieten dominieren Braunerden mit mässigem Wasserspeichervermögen und normaler Durchlässigkeit. Nur die Landnutzung unterscheidet sich markant mit praktisch vollständiger Bewaldung im Sperbelgraben und nur etwa 50%iger Waldbedeckung im Rappengraben. In beiden Gebieten herrschen leicht verzögert bis verzögert reagierende Flächen (AT2 und AT3, ca. 95%) vor (Abbildung 6). Die Abflussreaktion ist daher ziemlich rasch und stark.

Das EZG der Reppisch bis Birmensdorf umfasst eine Fläche von 22 km^2. Davon sind 12 % Siedlungs-, 48 % Gras- und 38 % Waldflächen. Die Reppisch hat sich tief in das von Gletschern geprägte Tal eingeschnitten und teilweise steile, heute meist bewaldete Flanken geschaffen. Der Unterbau des EZG bildet die aus Sandsteinen und Mergeln aufgebaute Obere Süsswassermolasse (HANTKE et al. 1967). Im Grossteil des EZG liegen ausgedehnte Flächen mit normal durchlässigen und speicherfähigen Braunerdeböden. Von Stau-, Hang- oder von Grundwasser geprägte Böden mit mässiger Durchlässigkeit und mässigem Speichervermögen sind im Gebiet weniger stark verbreitet. Insgesamt überwiegen im EZG der Reppisch verzögert bis stark verzögert reagierende Flächen (AT3 und AT4, 71.4%; Abbildung 6). Die Abflussreaktion kann daher als mässig bis stark bezeichnet werden.

Der Dorfbach entwässert in Meilen ein EZG von 4.6 km^2 und mündet direkt in den Zürichsee (Abb. 5 rechts). Das EZG des Dorfbachs Meilen ist von der Oberen Süsswassermolasse geprägt (HANTKE ET AL., 1967; ZINGG, 1934). Es ist vor allem die Nagelfluh, welche den oberflächennahen Untergrund dominiert. Lokal tritt Würmmoräne auf. Insgesamt liegen im EZG ausgedehnte Gebiete mit normal durchlässigen und speicherfähigen Braunerdeböden. Der Anteil an vernässten Böden mit mässiger Durchlässigkeit und eher geringem Speichervermögen ist höher als in der Reppisch. Im EZG des Dorfbachs machen die Abflusstypen 1-3 (rasch, leicht verzögert und verzögert beitragende Flächen) einen Anteil von insgesamt 41.5% der EZG-Fläche aus, 58.5% der Fläche reagieren stark bis sehr stark verzögert auf Niederschläge (AT4 und AT5; Abbildung 6). Aufgrund dieser Flächenverteilung zeigt der Dorfbach eine mässige bis starke Reaktion auf Niederschläge.

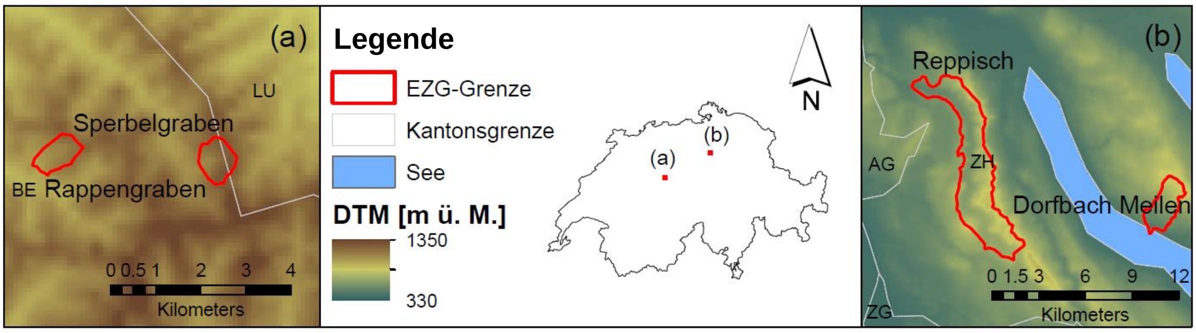

Abb. 5: Übersicht über die Untersuchungsgebiete. Quelle: BFS GEOSTAT/Bundesamt für Landestopografie swisstopo.

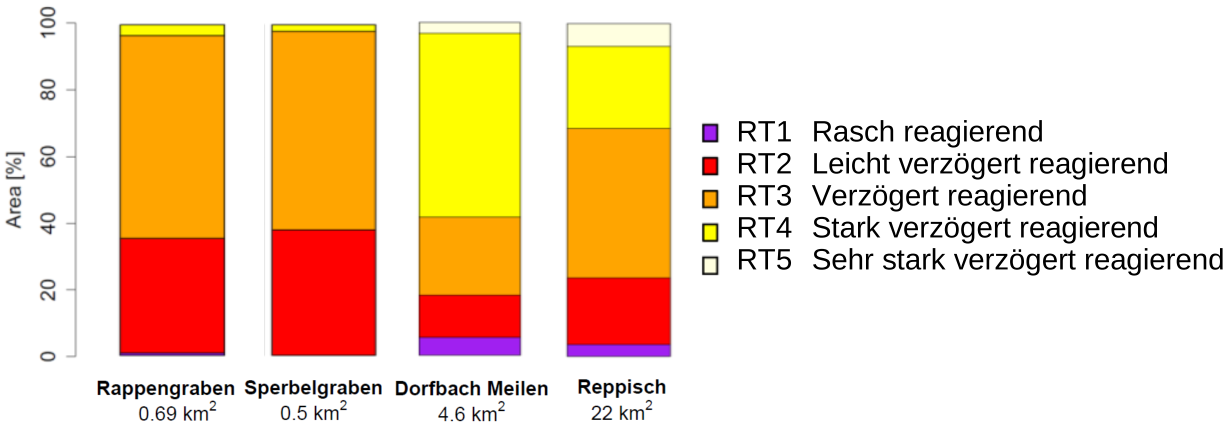

Abb. 6: Ausdehnung der Abflusstypenflächen in den vier Untersuchungsgebieten.

4.2 Vergleich zwischen prozessnahem und traditionellem PREVAH

Um den Mehrwert der Verwendung von ATK bei der Anwendung auf ungemessene Gebiete aufzuzeigen, wurde ein Vergleich zwischen dem traditionellen und dem prozessnahen Modell durchgeführt. Da im prozessnahen Modell die Abfluss-konzentration auf der Landoberfläche bis zum Auslass eines Teil-EZGs mit der Abflussbildung gekoppelt berechnet wird, muss bei Festlegung der Speicherkonstanten K0H und K1H die zeitliche Verzögerung des Abflusses verursacht durch die Fliesszeit von jeder Fläche zum Teil-EZG-Auslass (auch als Abflusskonzentration bezeichnet) berücksichtigt werden. Dies geschah mit einer Montecarlo (MC) Simulation, indem die Parameterwerte innerhalb der zuvor definierten Parameterbereiche optimiert wurden.

Dieselbe Vorgehens wurde für das traditionelle PREVAH vorgenommen, wobei die plausiblen Parameterbereiche für die MC Simulation in diesen Fall aus VIVIROLI et al. (2009b) stammen. Als Kalibrierungsgebiet wurde der Rappengraben gewählt, dessen Ausdehnung der durchschnittlichen Teil-EZG-Grösse entspricht. Die Simulationsperiode entspricht dem Monat Juni 2014. Da das prozessnahe Modul vor allem für die Simulation während und um grössere Ereignissen eingesetzt werden soll, ist beim Simulationsstart die Bestimmung einer Bodenfeuchte notwendig. Für diese Studie wurde die Bodenfeuchte für die untersuchten EZG aus kontinuierlichen, „gross-räumigen“ PREVAH-Simulationen mit einer Auflösung von 500 m täglich übernommen.

Für beide Modellversionen wurden die 10 besten Parameterkombinationen aus der Kalibrierungsphase ermittelt und auf die in Sektion 4.1 beschriebenen Untersuchungsgebiete angewandt. Die zeitliche Auflösung der Simulationen entspricht einer Stunde, der Auflösung der Niederschlagsdaten entsprechend. Um die optimierten Parameterbereiche in der prozessnahen Modellversion anwenden zu können, wurde jeder Zeitschritt in 6 Teilzeitschritte unterteilt (10 Minuten).

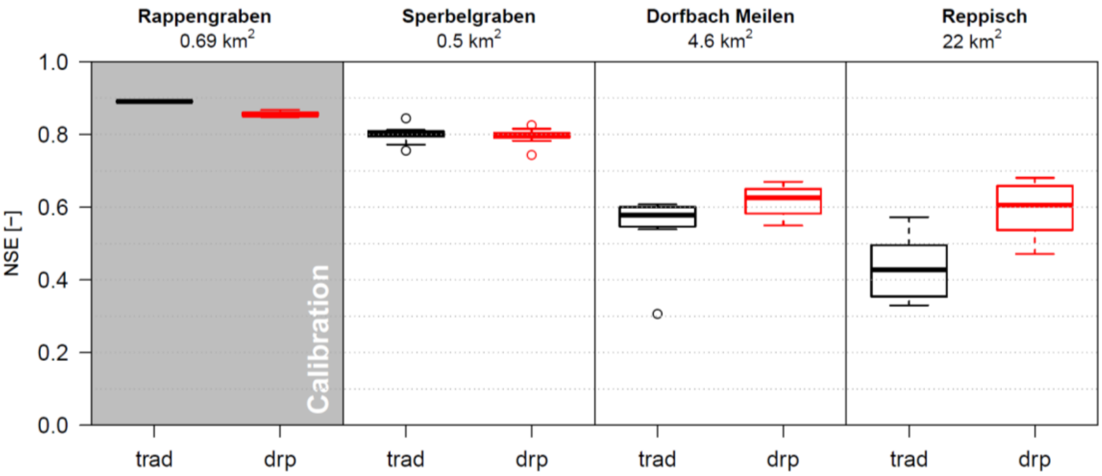

Abb. 7: Leistungsvergleich zwischen dem traditionellen PREVAH („trad“) und dem prozessnahen Abflussbildungsmodul („drp“) im Kalibrierungsgebiet (grauer Hintergrund) und auf die Verifikationsgebiete (weisser Hintergrund). Die Boxplots zeigen die Spannweite der Ergebnisse, die sich aufgrund der 10 besten Parameterkombinationen ergeben.

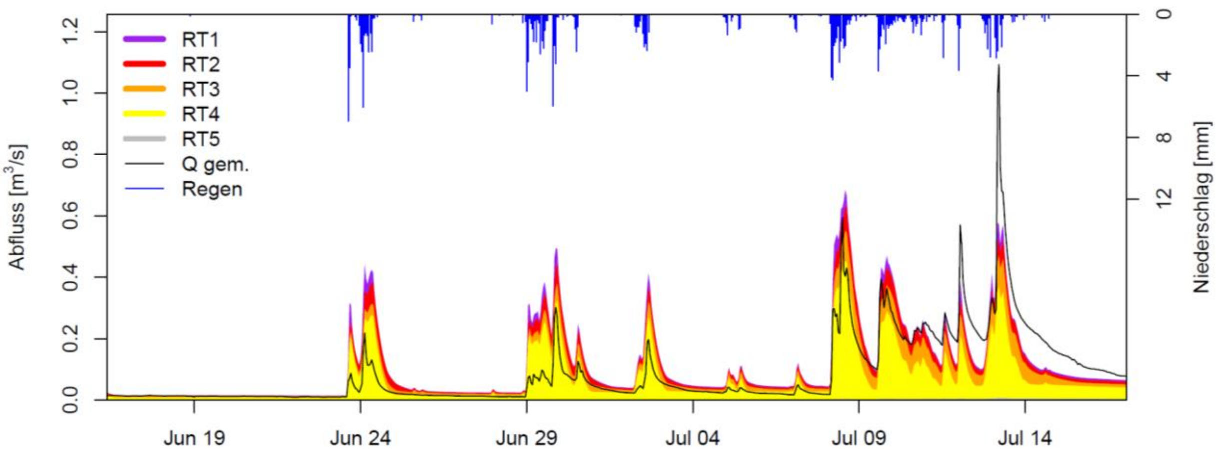

Abb. 8: Vergleich zwischen gemessener und simulierter Abflussganglinie mit dem Beitrag der verschiedenen Abflusstypenflächen für den Dorfbach Meilen. Für die Simulation wurde die beste Parameterkombination aus der Kalibrierung im Rappengraben verwendet.

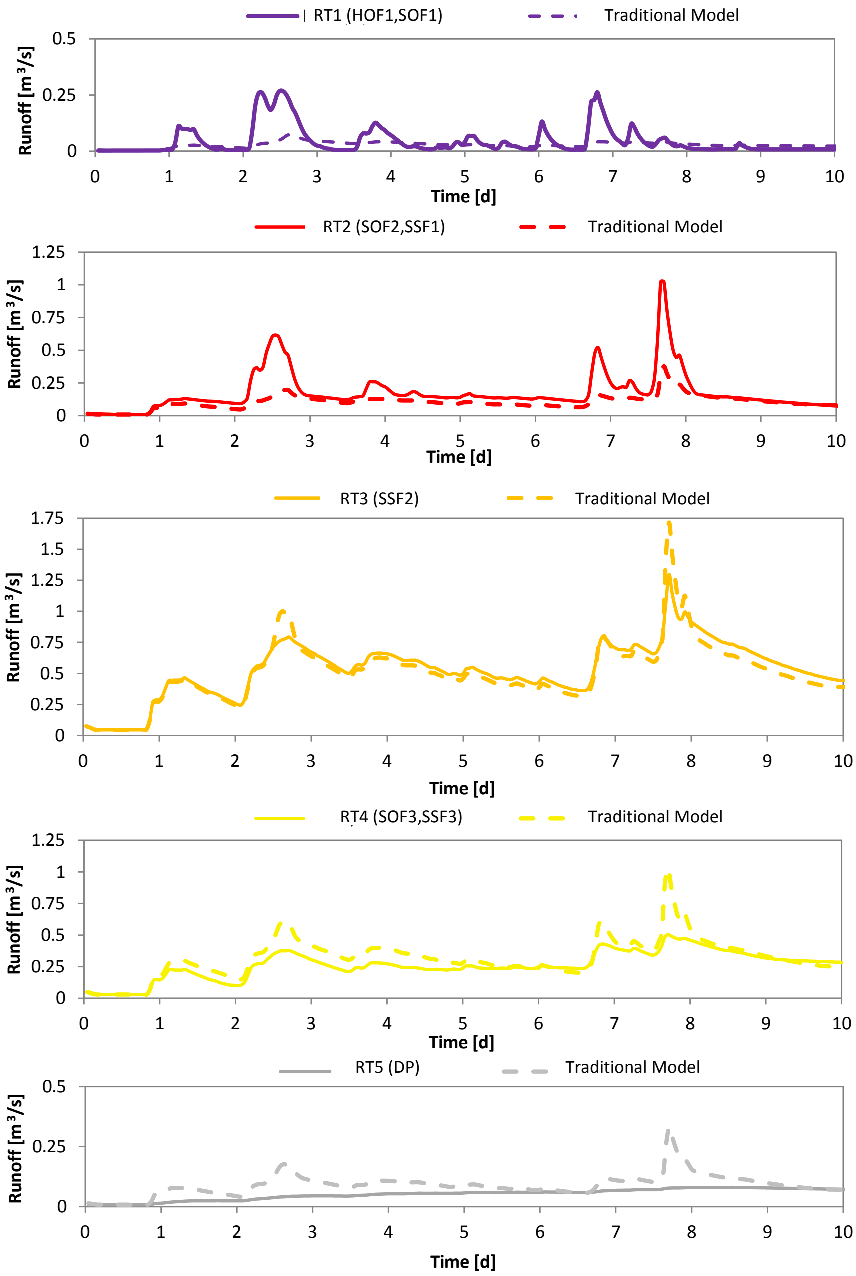

Abb. 9: Vergleich zwischen Abflussganglinien der unterschiedlichen Abflusstypen aus der Reppisch. Durchgehende Ganglinien zeigen den mit dem prozessnahen Abflussbildungsmodul berechneten Abfluss. Gestrichelte Linien zeigen die mit dem traditionellen PREVAH simulierte Ganglinie. Verändert nach BUSS (2014).

Die Ergebnisse zeigen, dass die Modelle in den zwei kleinen EZG sowohl in der Kalibrierungsphase als auch in der Validierungsphase eine ähnliche Güte aufweisen. Die Simulationen in den beiden grösseren EZG konnten nur mit einer weniger guten Performance durchgeführt werden (Abbildung 7). Mögliche Gründe dafür lassen sich anhand von Abbildung 8 erahnen. Eine bedeutende Rolle in den Berechnungen nehmen sicherlich die Speicherkonstanten K0H und K1H ein. Sie wurden im meist sehr steilen Gebiet des Rappengraben kalibriert und dann auf die flacheren mittelländischen EZG der Reppisch und des Dorfbaches Meilen übertragen. Die zu rasche Reaktion im Dorfbach Meilen lässt sich teilweise auf die sehr rasch entwässernden Speicher aus dem Rappengraben zurückführen. Zudem ist zu berücksichtigen, dass eine sinnvolle Kali-brierung der Speicherkonstanten nur für die zwei im Rappengraben dominierenden Abflusstypen 2 und 3 (vgl. Abbildung 6) möglich war. Die Niederschlagsdaten und die Anfangsbedingungen können zusätzliche Quellen für Unsicherheiten sein. Die Unter-schätzung der Abflussspitze am 13. Juli lässt sich z.B. durch einen ungenauen Niederschlagsinput erklären.

Jedenfalls zeigt das prozessnahe Modell im Vergleich zu dem traditionellen PREVAH sowohl im Dorfbach Meilen als auch in der Reppisch eine bessere Vorhersagefähigkeit (Abbildung 7). Mit dem neuen Modell liessen sich die Abflussprozesse besser nachbilden als mit dem herkömmlichen Modell (Abbildung 9). Im Vergleich zum traditionellen PREVAH sind die berechneten Abflussspitzen höher für schnell und leicht verzögert beitragende Flächen, während sie für stark verzögert und nicht beitragende Flächen gedämpfter sind.

5 Schlussfolgerungen und Ausblick

Ziel dieser Studie war, den Mehrwert eines Niederschlag-Abflussmodelles aufzuzeigen, das räumlich verteilte Informationen zu den dominanten Abflussprozessen verwendet. Das prozessnahe Abflussbildungsmodul, das zu diesem Zweck entwickelt wurde, greift auf Parameter zurück, die durch die Nachrechnung von Beregnungsversuchen festgelegt wurden. Bei diesem ersten Versuch zeigt das Modell in der Kalibrierungsphase eine zum traditionellen, kalibrierten PREVAH vergleichbare Leistung. In ungemessenen Gebieten lassen sich die Abflüsse mit dem neuen Modell hingegen zuverlässiger berechnen.

Die Anfangsbedingungen können einen grossen Einfluss auf die Simulationsergebnisse haben. Deshalb ist es wesentlich, diese möglichst genau und realitätsnah festzulegen. Eine Schätzung der Feldkapazitäten aus der Abflusstypenkarte, die bereits hochaufgelöste Informationen bezüglich des Speicherverhaltens beinhaltet, könnte die Initialisierung des neuen Abflussbildungsmodells noch verbessern.

In einem nächsten Schritt soll das prozessnahe Modell so umgeschrieben werden, dass die Abflussbildung und die Abflusskonzentration entkoppelt werden. Dies ermöglicht es erst, den Einfluss der Verteilung der Abflussprozesse auf die Abflussganglinie zu rekonstruieren und die definierten Parameter direkt auf ungemessene Gebiete zu übertragen. Dazu könnte die Erstellung einiger Übertragungsfunktionen dienen, die Speicherkonstanten mit Gebietseigenschaften oder Landschaftstypen zu verknüpfen.

Danksagung

Die Autoren bedanken sich beim Bundesamt für Umwelt (BAFU) für die Finanzierung der vorliegenden Studie und bei der MeteoSchweiz für die Bereitstellung der meteorologischen Daten.

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AII Operational application of a process-based runoff generation module in the Swiss Alps and Pre-Alps

This study presents a preliminary operational application of RGM-PRO and is based on the Master Thesis of Christoph Horat (IAC-ETHZ), who performed his work between August 2016 and February 2017 at WSL, under the supervision of Heini Wernli (IAC-ETHZ), Dr. Massimiliano Zappa (WSL) and myself. An adapted version of this study will be submitted for publication in Natural Hazards and Earth System Sciences. In the following, an extended summary of the study is presented.

Christoph Horat[a], Manuel Antonetti[b,c], Heini Wernli[a], and Massimiliano Zappa[b]

[a] Institute for Atmospheric and Climate Science, ETH Zürich, Zurich.
[b] Swiss Federal Research Institute WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland.
[c] Department of Geography, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland.

Abstract

Flash floods evolve rapidly during and after heavy precipitation events and represent a risk for society, especially in mountainous areas. Knowledge on meteorological variables and their temporal development is often not sufficient to predict their occurrence. Therefore, information about the state of the hydrological system derived from hydrological models is used. These models rely however on strong assumptions and need therefore to be calibrated. This prevents their application on catchments, where no runoff data is available.

Here we present a flash-flood forecasting chain including: (i) a nowcasting product which combines radar and rain gauge rainfall data (CombiPrecip), (ii) meteorological data from numerical weather prediction models at currently finest available resolution (COSMO-1, COSMO-E), (iii) operationally available soil moisture estimations from the PREVAH hydrological model, and (iv) a process-based runoff generation module with no need for calibration (RGM-PRO). This last component uses information on the spatial distribution of dominant runoff processes (DRPs) which can be derived with different mapping approaches, and is parameterised a priori based on expert knowledge.

First, we compared the performance of RGM-PRO with the one of a traditional conceptual runoff generation module for several events on the Emme catchment in the Pre-Alps, as well as on their nested catchments. Different DRP-maps are furthermore tested to evaluate the sensitivity of the forecasting chain to the mapping approaches. Then, we benchmarked the new forecasting chain with the traditional chain used on the Verzasca catchment in the Alps.

The results show that RGM-PRO performs similarly or even better than the traditional calibrated conceptual module on the investigated catchments. The use of strongly simplified DRP mapping approaches still leads to satisfying results, mainly due to the fact that the largest uncertainty source is represented by the meteorological input data. On the Verzasca catchment, RGM-PRO outperformed the traditional forecast chain in terms of mean absolute error, independently from the lead time and threshold quantile, whereas the Brier Skill Score did not show any clear preference. Probabilistic input data led generally to better results compared with those obtained with deterministic forecasts.

Introduction

Flash floods evolve rapidly during and after heavy precipitation events and represent a risk for society, especially in mountainous areas (Liechti et al., 2013). To predict timing and magnitude of peak runoff, it is common to couple meteorological and hydrological models in a forecasting chain (Zappa et al., 2011). However, hydrological models rely on strong simplifying assumptions and usually need to be calibrated. This prevents their application in catchments where no runoff data is available.

The following research questions have been addressed.

1. Is the process-based forecasting chain sensitive to process maps with different involvement of expert knowledge?
2. Does it perform better than a conventional forecasting chain, where the hydrological model relies on calibration?
3. Is the predictive power improved compared to the one of an operational benchmark forecast?
4. Which meteorological data – deterministic or probabilistic – produces better results?

Material and methods

The process-based flash flood forecasting chain introduced for this study consists of:

i. CombiPrecip data, i.e. a nowcasting product which combines radar and rain gauge rainfall data (Sideris et al., 2014), used for initialisation;
ii. Meteorological data from state-of-the-art numerical weather prediction models (COSMO-1, COSMO-E);
iii. Operationally available soil moisture estimations from the PREVAH hydrological model (Zappa et al., 2014);
iv. The process-based runoff generation module RGM-PRO with no need for calibration (cf. chapter 3.3). RGM-PRO is then parametrised a priori based on the results of sprinkling experiments (Scherrer et al., 2007);
v. Process maps, i.e. maps showing the spatial distribution of dominant runoff processes within a catchment (cf. chapter 3.2). Two different mapping approaches were used for this case study, i.e. the method with high involvement of expert knowledge based on Margreth et al. (2010) and Schmocker-Fackel et al. (2007), from here on referred to as SF07, and one with low involvement of expert knowledge (Müller et al., 2009), referred to as MU09.

This prediction chain has been evaluated using data from April to September 2016 in two medium-size Swiss basins prone to flash floods: the Emme up to Emmenmatt in the Swiss Pre-Alps and the Verzasca in the southern Swiss Alps (Figure 1). In the Emme catchment, two novel forecasting chains were set up with two different maps of runoff types, which allowed a sensitivity analysis of the forecast performance on mapping approaches. Furthermore, special emphasis was placed on the predictive power of the new forecasting chains in nested subcatchments when compared with a prediction chain including a conventional hydrological model relying on calibration. In the Verzasca river basin, an operational benchmark forecast already exists, consisting of a conventional hydrological model initialised with pluviometer data and forced with precipitation predictions from COSMO-1 and COSMO-E [1]. Therefore, the main research question in this area was to compare the skill of the novel prediction system to the one of the operational benchmark forecast.

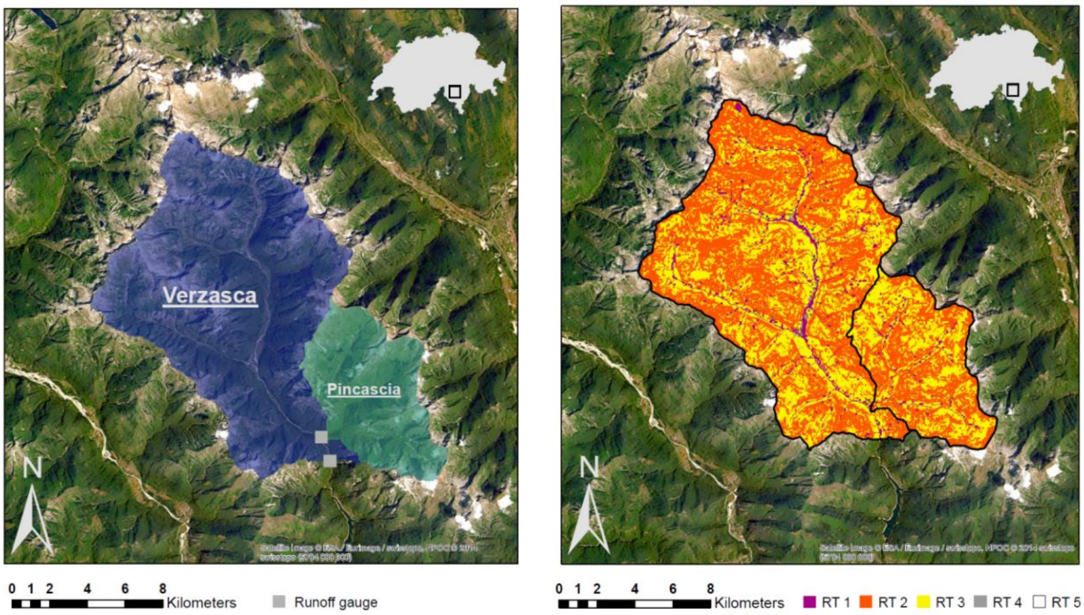

Figure 1 Location of the Verzasca catchment and the Pincascia subcatchment (left) and process map based on Müller et al.'s (2009) mapping approach.

To address the first research question, process-based forecasting chains were set up in the Emme catchments based either on MU09 map (DRP-mu-C1 and DRP-mu-CE) or on SF07 map (DRP-ma-C1 and DRP-ma-CE). The comparison among these chains will show possible advantages of including a higher amount of expert knowledge in the process map for forecasting purposes.

With regard to the second research question, two additional chains were built on the Emme catchment with the calibrated hydrological model PREVAH (PRE-C-C1 and PRE-C-CE). The calibrated parameter set resulted from the 10 runs with highest KGE out of 4’000 runs of a Monte Carlo simulation performed for the largest runoff event measured at Emmenmatt in 2016, which occurred on the 14th of May. Comparison of RGM-PRO based chains with the ones based on the calibrated PREVAH will indicate whether a hydrological model integrating knowledge on DRPs can compete with a calibrated hydrological model in forecast mode.

In the Emme basin, all forecasting chains were relying on model initialisation with CombiPrecip and soil moisture data from PREVAH simulations. To ensure the lowest influence of initial conditions on predictions, for each forecasting chain, the onset of initialisation was identified with the time step with the lowest observed runoff in the last five days prior to the forecast.

To address the third research question, RGM-PRO was set up with MU09 maps for the Verzasca catchment, where an operational hydrological forecasting system run by WSL already exists (Zappa et al., 2011, 2013) . The process based chain was therefore combined with COSMO-1 and COSMO-E, building the forecasting chains DRP-C1 and DRP-CE. These were compared with the operational forecasting system, which is based on the traditional, calibrated PREVAH, and is initialised with rain gauge data interpolated with a inverse distance weighting method (Andres et al., 2016). Its combination with COSMO-1 and COSMO-E is from here on referred to as TRAD-C1 and TRAD-CE. Comparing the process-based forecasting chain with the traditional one will therefore highlight possible benefits of including knowledge on DRPs into hydrological modelling. Differences may however arise due to the use of CombiPrecip instead of pluviometer data for model initialisation.

Finally, to address the fourth research question, a comparison of forecasting chains fed with either COSMO-1 or COSMO-E data will show whether high resolution deterministic or probabilistic NWP data is favourable.

At each alert date, deterministic forecasting chains were run with the eight COSMO-1 forecasts available on that day and probabilistic chains with the two COSMO-E forecasts. This resulted in a total of 5'280 hours of forecast for each forecasting chain based on COSMO-1 and yielded 5'016 forecast-observation pairs for each chain that was relying on COSMO-E in each basin. For further details on this operational application of RGM-PRO see Horat (2017).

Verification Methods

For the verification of the deterministic forecasts, the Kling-Gupta efficiency (KGE) was computed (Gupta et al., 2009), which is a decomposition of MSE into a linear correlation, a bias, and a variability of flow component. The ideal value of KGE is one and positive values indicate a benefit compared with a reference forecast.

Deterministic continuous forecasts were also turned into deterministic forecasts for dichotomous predictands, where event (1) and non-event (0) cases are distinguished with a threshold. This allowed the Brier skill score (BSS), the probability of detection (POD), and the false alarm ratio (FAR) to be calculated. The BSS was computed in the same way as the MSE but with values of 0 or 1. It therefore measures correspondence of threshold exceedance for forecast and observation but does not take into account magnitude of difference. A perfect prediction delivers a value of one for BSS. The POD is the number of times a threshold exceedance was correctly forecast ("hit") divided by the number of times a threshold exceedance occurred. The FAR is the number of cases where a threshold exceedance was forecast but did not occur ("false alarm"), divided by the total number of forecast threshold exceedances. A perfect forecast has a POD of 1 and a FAR equal 0.

With regard to probabilistic forecasts for dichotomous predictands, they were turned into deterministic forecasts for dichotomous events with varying probability thresholds. A probability below the threshold was turned into a 0 % likeliness and a probability above the threshold was turned into a 100 % likeliness for event-occurrence. For various probability thresholds, POD and FAR were calculated and visualised as a curve in a receiver operating characteristics (ROC) diagram. The area under a ROC curve (ROCa) is a measure of discrimination and is 1 for a perfect forecast and 0.5 for a not skilful forecast.

To assess the sampling uncertainty of skill score computations, the bootstrapping approach described by Efron (1979) was used, which enabled visualisation of skill scores as boxplots. As time windows of 6 to 24 hours were considered, assumption of independence may not be strictly valid in our case and a moving window bootstrap could have been more appropriate. However, this method was not implemented to ensure comparability with Liechti et al. (2013), who evaluated daily maxima.

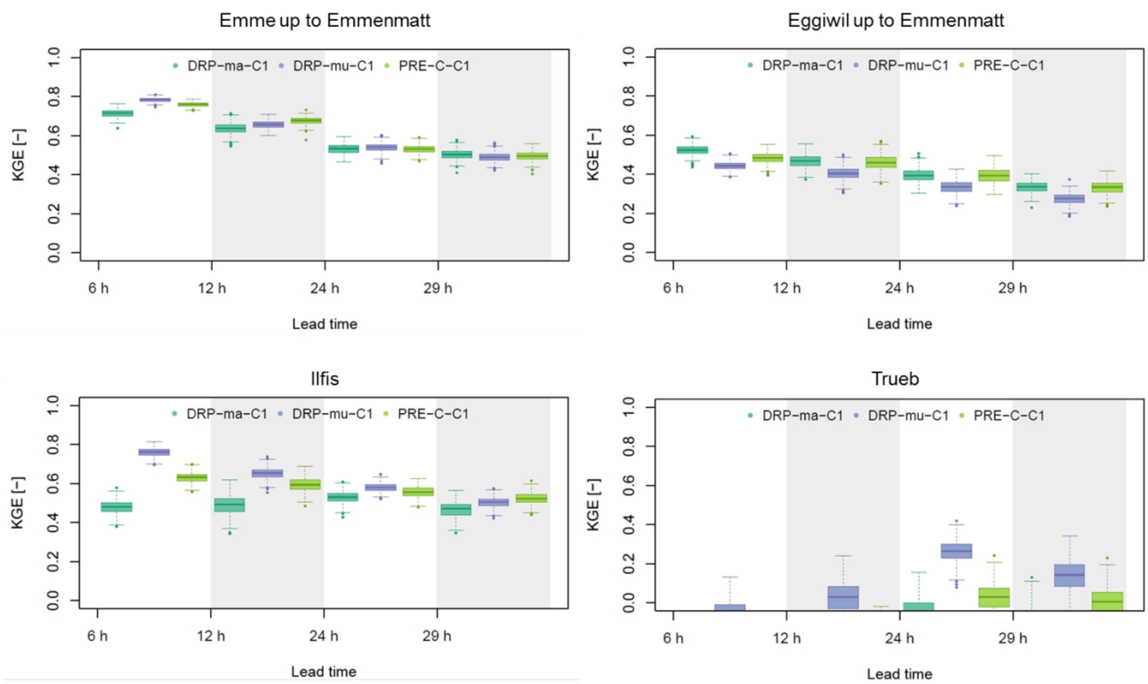

Figure 2 KGE for Emmenmatt (a), Eggiwil (b), Ilfis (c) and Trueb (d) as a function of lead time for DRP-ma-C1 (dark green), DRP-mu-C1 (blue) and PRE-C-C1 (light green). The boxplots represent the sampling uncertainties of the score computations obtained with bootstrapping (6 h window).

Finally, the peak-box approach (Zappa et al., 2013) was used for estimating timing and magnitude of runoff peak for probabilistic forecasts. For every member of the ensemble in hydrographs, magnitude and timing of respective peak flow was computed, which lead to 21 peaks for COSMO-E. A so-called peak-box was then drawn into the ensemble of hydrographs as a rectangle confined to the left by the earliest predicted, to the right by the latest predicted, to the bottom by the lowest predicted, and to the top by the highest predicted peak. The best estimate for the peak was then chosen as the point with the 50 %-quantile in terms of peak timing (t50) as x-coordinate and with the 50 %-quantile in terms of peak magnitude (p50) as y-coordinate. For further details on the peak-box method please refer to Zappa et al. (2013).

Results

KGE values offer an evaluation of the simulations obtained with the forecasting chains from a hydrological point of view. When considering the Emmenmatt catchment and its subcatchment up to Eggiwil, the KGE show that there is skill for all deterministic forecasting systems and all investigated lead times (Figure 2a and Figure 2b), and that this skill decays over time. In both catchments, no clear preference for one forecasting chain can be found. On the Ilfis catchment, DRP-mu-C1 is the best and DRP-ma-C1 the worst performing forecasting chain, apart from a lead time of 29 hours, where PRE-C-C1 is best in terms of KGE. In the Trueb basin, there is little skill for DRP-mu-C1 at lead times of 12, 24 and 29 hours and for PRE-C-C1 at 24 and 29 hours lead time. Apart from the Eggiwil catchment, DRP-mu-C1 performed slightly better than DRP-ma-C1 in most cases. However, relative differences between the approaches are usually small and uncertainty bars overlap.

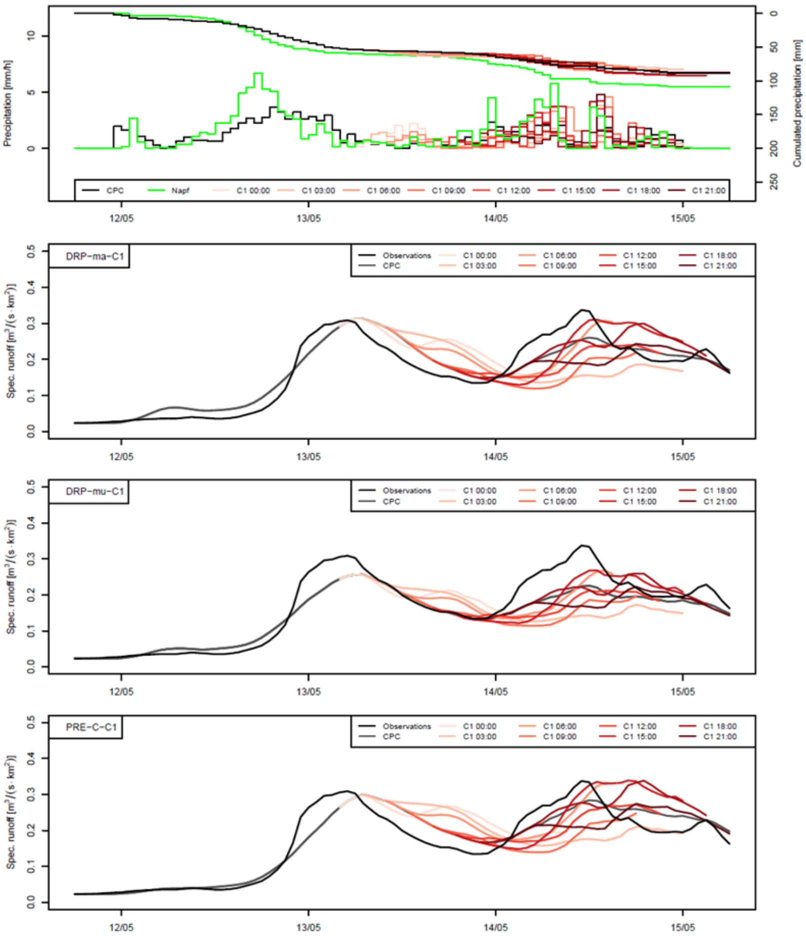

Figure 3 Flood predictions with DRP-ma-C1, DRP-mu-C1, and PRE-C-C1 for Emmenmatt with eight initialisations each on alert date of 13/5/2016. Catchment precipitation predictions from COSMO-1, measurements from Napf station and CombiPrecip are depicted in the upper panel.

Visual inspection of events represents a very valuable complement to statistical evaluation and gives to forecasters and users a better intelligible way to get a feeling on the quality of their systems. Figure 3 depicts deterministic flood predictions of DRP-ma-C1, DRP-mu-C1 and PRE-C-C1 in the Emmenmatt basin, as well as the temporal evolution of precipitation from the 11th to the 15th of May 2016. This was the largest event in the Emmenmatt catchment investigated in this study and also the time period for which PRE-C-C1 (and PRE-C-CE) was calibrated. In terms of COSMO-1 precipitation forecasts, cumulated predicted rainfall reveals to be in good agreement with CombiPrecip data. Main phases of precipitation input are in the late evening of May 12 and in early morning of May 14. None of the three prediction chains is really able to catch the quickly rising hydrograph during the initialisation period with CombiPrecip, although performance is satisfying. The simulated first peak of DRP-ma-C1 and PRE-C-C1 is relatively good in terms of volume, whereas DRP-mu-C1 underestimates it. These characteristics appear also in forecast mode, where the highest forecasted peak of DRP-ma-C1 and PRE-C-C1 almost reach the observed second peak, whereas DRP-mu-C1 substantially underestimates it. Overall, performance of DRP-ma-C1 and PRE-C-C1 is comparable in this example. Comparing the two process-based chains reveals that SF07 maps generate higher peaks than the MU09 maps. Spread in hydrographs resulting from the eight COSMO-1 initialisations on that day is considerable, especially for the strongly reacting DRP-ma-C1 and PRE-C-C1.

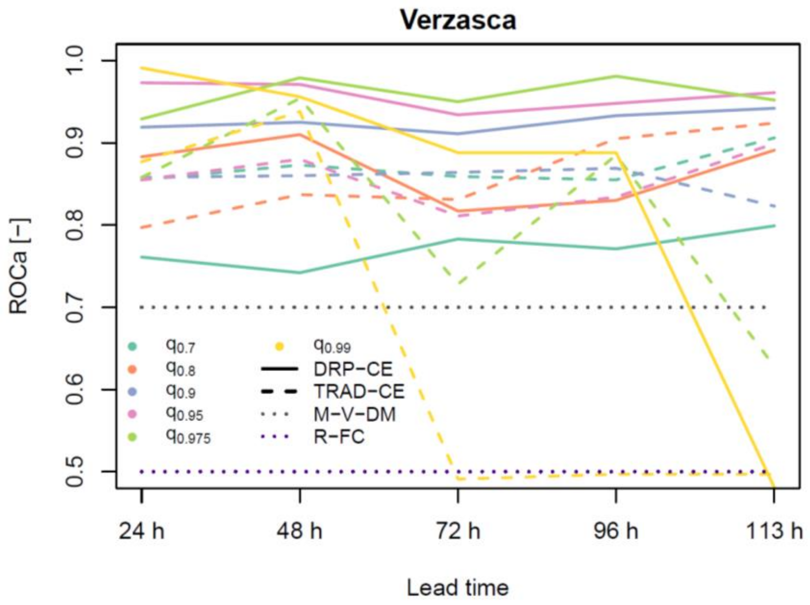

Figure 4 Evolution of ROCa for probabilistic DRP-CE (solid) and TRAD-CE (dashed) as a function of lead time for Verzasca catchment for several quantiles. Grey dotted line (M-V-DM) indicates ROCa of 0.7, which is the minimum value that is still useful for decision makers (Buizza et al., 1999). An unskilful forecast would yield a ROCa of 0.5 (Wilks, 2011), which is indicated by the purple dotted line (R-FC). A window of 24 hours was taken for the computations.

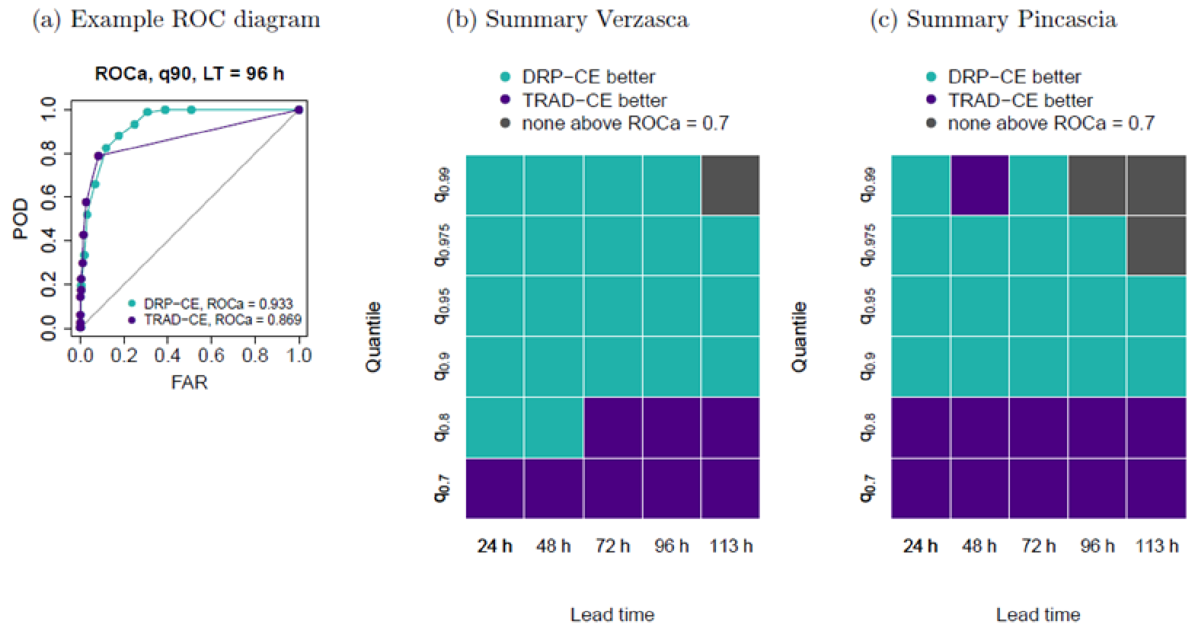

Figure 5 Summaries of ROCa for Verzasca (b) and Pincascia (c) as a function of lead time and threshold quantile for TRAD-CE and DRP-CE. Blue colour indicates that ROCa of DRP-CE is higher, whereas purple colour implies that TRAD-CE performs better. Grey shading indicates that none of the forecasting chains has ROCa higher than 0.7, which is considered to be the minimum value useful for decision makers (Buizza et al., 1999). Summaries are based on ROC diagrams, of which an example is shown in (a) for the Verzasca basin: ROC curve for TRAD-CE (purple) and DRP-CE (blue) are indicated for a lead time of 96 hours and q0.9 threshold quantile with corresponding ROCa. Please note that steps in probability thresholds of 0.1 are used. A window of 24 hours was taken for the computations.

For the Verzasca catchment, values of ROCa only show a strong decreasing tendency for increasing lead times for the $q_{0.975}$ and $q_{0.99}$ threshold quantiles (Figure 4). The forecasts are of use for decision makers up to 96 hours for DRP-CE and up to 48 hours for TRAD-CE when considering the $q_{0.99}$ threshold quantile. Values of ROCa for all other quantiles never drop below the minimum value useful for decision makers, apart from TRAD-CE for a lead time of 113 hours and the $q_{0.975}$ threshold quantile.

Summaries of ROCa depict a clear preference for DRP-CE over TRAD-CE for the highest quantiles in both Verzasca and Pincascia catchments (Figure 5). The only exception to this is represented by the $q_{0.99}$ threshold quantile for 48 hours lead time in the Pincascia basin. In contrast, TRAD-CE is favoured for the two lowest quantiles. Preference of DRP-CE over TRAD-CE is more strongly pronounced in Verzasca catchment compared with Pincascia. Furthermore, forecasts are useful for more threshold quantiles and lead times in the Verzasca basin compared with the Pincascia catchment. However, predictions of longest lead times and highest threshold quantiles are not of use in both catchments.

In Figure 6, probabilistic flood forecasts with DRP-CE and TRAD-CE of an event that occurred on June 2016 are shown. For DRP-CE, the observed hydrograph lies completely within the ensemble spread, whereas the runoff peak is not captured by TRAD-CE. In terms of peak-box method, the timing of best peak estimate is very good for both forecasting chains, but the magnitude is substantially underestimated. Considering the complete re-simulation of the event with CombiPrecip data, RGM-PRO performed better than the calibrated traditional PREVAH forced with pluviometer data. As in the case of deterministic forecasts forced with COSMO-E, DRP-CE is found to react quicker and more strongly on rainfall compared with TRAD-CE.

The forcing data from deterministic and probabilistic forecasts performed differently (Figure 7 and Figure 8). In all catchments, there is in general a decrease of BSS with lead time. Furthermore, there is less skill for increasing threshold quantiles. In all basins, no increase of uncertainty with lead time is visible and spread of forecasting chains relying on CE is larger than for approaches based on C1. The ensemble approach is however always better than its respective deterministic counterpart with very few exceptions. Deterministic forecasting chains are most competitive at short lead times, whereas for lead times of 24 and 29 hours the skill of the ensemble approach is substantially larger. In most cases, however, uncertainty bars of BSS overlap.

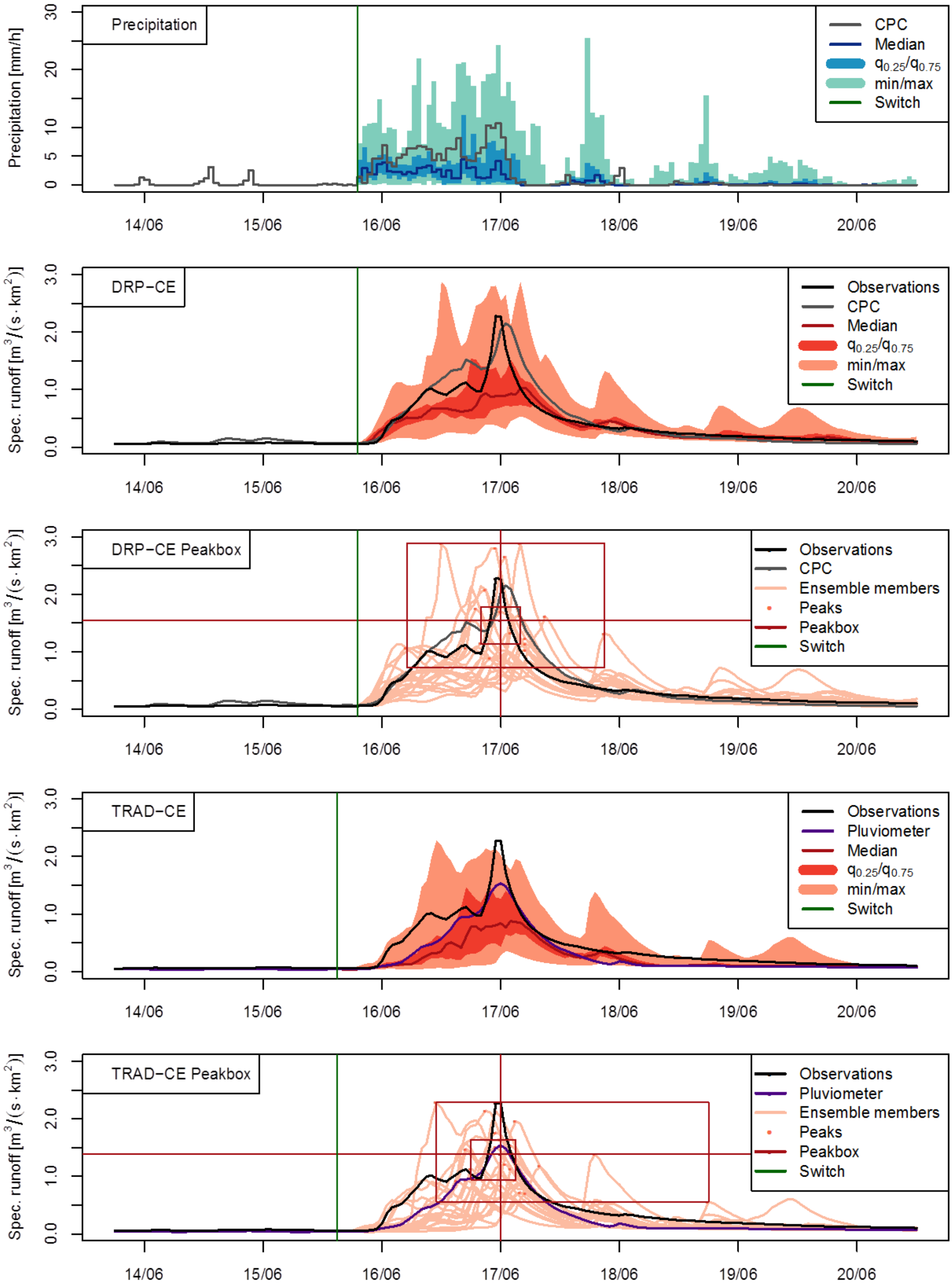

Figure 6 Ensemble flood prediction for the largest event in Verzasca basin investigated in this study with switch to forecast mode at 19:00 on 15th of June, 2016. Probabilistic precipitation forecasts from COSMO-E and CombiPrecip is shown in top panel. Second and fourth panel depict ensemble area plots and third and fifth panel show the peak-box approach for DRP-CE and TRAD-CE, respectively.

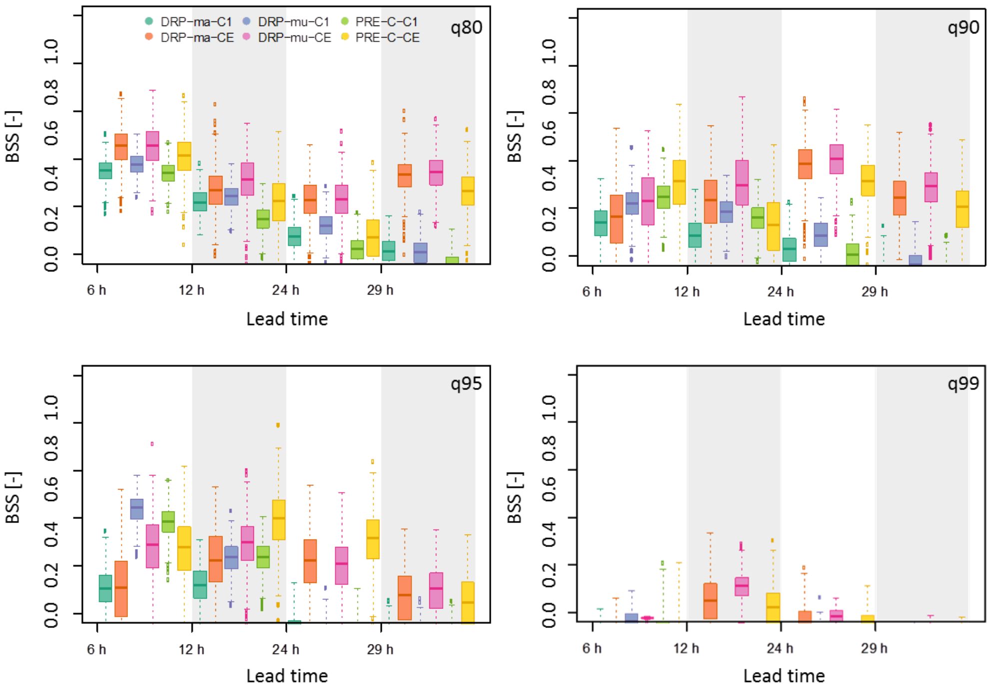

Figure 7 Comparison of BSS on the Emmenmatt catchment for the deterministic forecasting chains DRP-ma-C1, DRP-mu-C1, PRE-C-C1 and for the probabilistic DRP-ma-CE, DRP-mu-CE, PRE-C-CE as a function of lead time for several threshold quantiles. The boxplots represent the sampling uncertainties of the score computations obtained with bootstrapping of a 6 hours window.

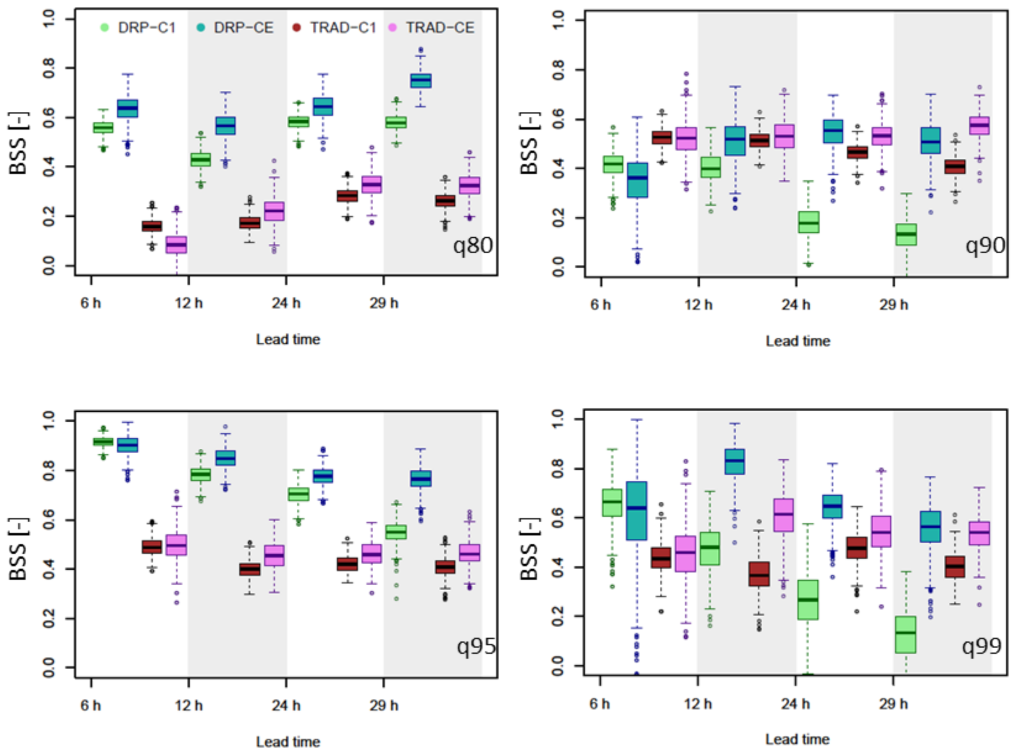

Figure 8 Comparison of BSS on the Verzasca catchment for the deterministic forecasting chain DRP-C1 and TRAD-C1, and for the probabilistic DRP-CE and TRAD-CE as a function of lead time for several threshold quantiles. The boxplots represent the sampling uncertainties of the score computations obtained with bootstrapping of a 6 hours window.

Discussion

Effect of different DRP mapping approaches in the Emme catchment

No clear preference for using either SF07 or MU09 map in flash flood forecasting chains was found, with uncertainty bars overlapping in most cases. In terms of potential skill, measured in ROCa, the SF07 mapping approach is best in most cases for all catchments. Case studies revealed that DRP-ma-C1/CE react more intensely on precipitation in comparison with DRP-mu-C1/CE. This does not necessarily lead to faster occurring peaks, but to peaks that are higher in magnitude. This is in good agreement with the different distribution of processes derived with the two mapping approaches: as the MU09 method classifies much more deep percolation (RT5), there is less simulated water at the runoff gauge. In terms of peak timing, there is not much difference between process-based forecasting chains, which could be ascribed the fact that the MU09 approach originated higher fractions of fast contributing areas (RT1), leading to compensation effects. Both visual inspections of hydrographs and skill scores reveal very similar performance of both approaches which is remarkable when taking into account how distinct the two maps look (not shown, see Horat, 2017). A reason that difference may not be as large as expected could be that – in agreement with Zappa et al. (2011) – meteorological uncertainties are dominant, and uncertainty in DRP mapping is of minor importance in forecast mode.

Effect of integrating knowledge on DRP into hydrological modelling

In the nested catchments of the Emme basin, the comparison of the two process-based forecasting chains with the one including a calibrated hydrological model showed comparable performance in terms of KGE, POD, BSS and ROCa in Emmenmatt, Eggiwil and Ilfis catchment. For lowest threshold quantiles, FAR of PRE-C-C1 is substantially larger than for the process-based forecasting chains in all catchments. In the Trueb catchment, performance of process-based forecasts is substantially better than the one of PRE-C-C1/CE. This is in accordance with Antonetti et al. (2016a), who stated that process-based forecasting chains should be advantageous especially in small nested sub-catchments and not in main catchments where calibration was made for.

With regard to the Verzasca catchment, the process-based forecasting chains were able to react faster on precipitation input than the traditional forecast system. This could be due to the pre-moistening phase of the traditional PREVAH, as the soil moisture storage content must rise before strong runoff peaks can be simulated. Furthermore, as the process-based forecasting chains reacted more intense on rainfall input, higher peaks in runoff but also larger uncertainties for the ensemble approach were reached. Although the use of information about DRP decreases hydrological model parameter uncertainty, as found by Antonetti et al. (2016b), it does not decrease total uncertainty in forecast mode.

In terms of ROCa, a striking preference for DRP-CE over TRAD-CE for high threshold quantiles relevant for flash floods in both catchments (Verzasca and Pincascia) and for all lead times was found. However, it is not clear whether this is due to the usage of RGM-PRO instead of traditional PREVAH or rather due to the inclusion of CombiPrecip instead of pluviometer data. Conversely to what speculated by Antonetti et al. (2016), the process-based forecasts were not of advantage in the nested Pincascia basin, as the traditional forecast was more competitive in terms of ROCa and also BSS. However, for the process map of the Verzasca basin, which was derived using simplified methodology of Müller et al. (2009), there is some potential for improvement. For instance, the fact that small patches of fast areas appear within slower regions represents an unrealistic feature, as re-infiltration would happen. This could be avoided by either applying a filter or with more expert knowledge and field work.

Effect of using a meteorological ensemble

In accordance with Addor et al. (2011), Liechti et al. (2013) and others, a clear preference for the probabilistic approaches in all catchments and for all forecasting chains is found. Forecasts based on COSMO-1 with a mesh size of 1.1 km, should theoretically be preferred to COSMO-E having a resolution of only 2.2 km, as a smaller grid size allows for better representation of convective systems responsible for flash flood (Collier, 2007). However, COSMO-E data proved to be more valuable in this thesis, as it tackles meteorological uncertainty with 21 ensemble members. Furthermore, there was a stronger decrease in skill with increasing lead time for the deterministic than for the probabilistic approach, which was found also by Addor et al. (2011). Deterministic forecasting chains are most competitive for very short lead times. This is also due to the fact that the skill of probabilistic prediction systems is not always maximum for shortest lead time but sometimes later, as it takes some time until spread of ensembles builds up (e.g. Schaake et al., 2007).

Limitations of this study

In general, it is the Trueb basin which has the most peculiar findings and reveals the largest sampling issues. However, large uncertainties are linked with the measured runoff data (Scherrer AG, 2012). As a further limitation of this thesis, one has to be aware that not only flash floods are investigated but also heavy runoff events that develop over days, which is also the case in the study of e.g. Liechti et al. (2013). To treat flash floods that evolve within minutes, which is part of the definition by Norbiato et al. (2008), a temporal resolution of one hour is not sufficient.

Conclusions

According to the research questions formulated above, the following findings can be reported:

1. The predictive power of the process-based forecasting chain is not sensitive to the amount of expert knowledge used for the hydrological classification. This is likely linked with compensation effects occurring within the hydrological model.
2. In the larger sub-basins of the Emme region, the process-based forecasting chains revealed comparable skill as the prediction system based on a conventional, calibrated hydrological model. In the smaller sub-basins, the process-based forecasting chains outperformed the conventional system, but no forecasting chain showed high skills.
3. In the Verzasca areas, the process-based forecasting chain was able to compete with the operational benchmark prediction system and was superior for high-flow situations. The process-based forecasting chain was able to react faster on precipitation in comparison with the traditional forecast.
4. For all forecasting chains, a clear preference for the use of meteorological ensembles was found.

Acknowledgements

This study is supported by the Swiss Federal Office for Environment (FOEN). MeteoSwiss is acknowledged for providing the rainfall data. Thanks to Michael Margreth and Simon Scherrer for providing the SF07 maps.

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Curriculum vitae

Manuel Antonetti

from Brunico (BZ), Italy

born on 4 June 1987 in Brunico (BZ), Italy

WORK EXPERIENCE

10/2013 – 9/2017	PhD candidate at the Swiss Federal Institute WSL, Mountain Hydrology and Mass Movements, Zürcherstrasse 111, CH-8903 Birmensdorf
5/2013 – 9/2013	Student assistant at Karlsruhe Institute of Technology (KIT) – Institute of Hydrology, Faculty of Engineering, Otto-Amman-Platz 1, D-76131 Karlsruhe

EDUCATION

10/2013 – 9/2017	Dissertation at the Swiss Federal Institute WSL and at the Department of Geography of the University of Zurich
2/2010 – 3/2013	University of Trento and Karlsruhe Institute of Technology (KIT) – Double-Master-Degree in civil and environmental Engineering – Specialisation in “Water and Environment”
9/2006 – 1/2010	University of Trento (I), Faculty of Engineering – Bachelor in environmental Engineering
9/2001 – 7/2006	Istituto Tecnico per Geometri “A. e P. Delai”, Bolzano (I) – Degree in surveying

PUBLICATIONS

Antonetti, M. and Zappa, M.: How can expert knowledge increase the realism of conceptual hydrological models? A case study in the Swiss Pre-Alps. Hydrol. Earth Syst. Sci. Discuss. doi: 10.5194/hess-2017-322, In review, 2017.

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CONFERENCE CONTRIBUTIONS

EGU General Assembly - April 2017 - Vienna (AT) - "How much expert knowledge is it worth to put in conceptual hydrological models?" - Poster presentation

EGU General Assembly - April 2016 - Vienna (AT) - "Comparing bottom-up and top-down parameterisations of a process-based runoff generation model tailored on floods" - Oral presentation

Convegno ARGEALP "Dissesto idrogeologico nell'arco alpino e prealpino: previsione, prevenzione e gestione dell'emergenza" - March 2016 - Lugano (CH) - "Il processo di generazione del deflusso durante le piene: simulazione e previsione con l'utilizzo di carte del processo di deflusso e curve IDF" - Oral presentation

4. Trierer Workshop zur Niederschlag-Abfluss-Modellierung - October 2015 - Trier (DE) - "Überprüfung eines prozessnahen Abflussbildungsmoduls auf der Hangskale und in klein- und mesoskaligen Gebieten" - Oral presentation

EGU General Assembly - April 2015 - Vienna (AT) - "Evaluating different mapping approaches of dominant runoff processes with similarity measures and synthetic runoff simulations" - Poster presentation